Glacial geomorphology of Teesdale, northern Pennines, England: implications for upland styles of ice stream operation and deglaciation in the British-Irish Ice Sheet

David J. A. Evans, Matthew Dinnage & David H. Roberts

Department of Geography, Durham University, South Road, Durham DH1 3LE, UK

Abstract

The glacial geomorphology of Teesdale and the North Pennines uplands is analysed in order to decipher: a) the operation of easterly flowing palaeo-ice streams in the British-Irish Ice Sheet; and b) the style of regional deglaciation. Six landform categories are: i) bedrock controlled features, including glacitectonic bedrock megablocks or 'rubble moraine'; ii) discrete mounds and hills, often of unknown composition, interpreted as weakly streamlined moraines and potential 'rubble moraine'; iii) non-streamlined drift mounds and ridges, representing lateral, frontal and inter-ice stream/interlobate moraines; iv) streamlined landforms, including drumlins of various elongation ratios and bedrock controlled lineations; v) glacifluvial outwash and depositional ridges; and vi) relict channels and valleys, related to glacial meltwater incision or meltwater re-occupation of preglacial fluvial features. Multiple tills in valley-floor drumlin exposures indicate that the subglacial bedform record is a blend of flow directions typical of areas of discontinuous till cover and extensive bedrock erosional landforms. Arcuate assemblages of partially streamlined drift mounds are likely to be glacially overridden latero-frontal moraines related to phases of "average glacial conditions" (palimpsests). Deglacial oscillations of a glacier lobe in mid-Teesdale are marked by five inset assemblages of moraines and associated drift and meltwater channels, named the Glacial Lake Eggleshope, Mill Hill, Gueswick, Hayberries and Lonton stages. The Lonton stage moraines are thought to be coeval with bedrock-cored moraines in the central Stainmore Gap and likely record the temporary development of cold-based or polythermal ice conditions around the margins of a plateau-based icefield during the Scottish Readvance.

Key words: British-Irish Ice Sheet; Palaeo-ice stream; North Pennines; drumlins; meltwater channels; glacitectonic rubble moraine

1. Introduction

The results of palaeoglaciological reconstructions of the last British–Irish Ice Sheet (BIIS), based on both field observations (Salt and Evans, 2004; Greenwood and Clark, 2008, 2009a,b; Hughes, 2008; Livingstone et al., 2008, 2012; Davies et al., 2009a; Evans et al., 2009) and numerical modelling (Boulton and Hagdorn, 2006; Hubbard et al., 2009), indicate that it was highly dynamic and drained by a number of oscillating and temporally cross-cutting ice streams, and associated with rapid switches in ice-flow direction driven by shifting ice-dispersal centres and ice divides. The central sector of the BIIS lay over the northern Irish Sea Basin and northern England and was characterized by the most complex changes in ice flow dynamics through the last glacial cycle, thereby playing a critical role in the spatial and temporal development of glacierization styles and ice stream locations (Livingstone et al., 2008, 2012; Evans et al., 2009). This is a reflection of the proximity to the major upland ice-dispersal centres of the Southern Uplands, Lake District, Cheviots and Pennines, which were the seeding points for upland ice masses that later expanded and coalesced to form ice sheet dispersal centres. This resulted in complex geomorphological signatures of former ice flow, including evidence for ice-flow directional change, ice-flow reversals and ice sheet marginal oscillations (cf. Trotter, 1929a; Hollingworth, 1931; Mitchell, 2007; Livingstone et al., 2008, 2012; Evans et al., 2009). Northern England is therefore a key area in terms of reconstructing the palaeo-dynamics of the BIIS through the last glacial cycle.

Despite recent advances in detailing the palaeoglaciological reconstructions over the Solway Lowlands, Eden Valley and Tyne Gap (Greenwood et al. 2007; Livingstone et al., 2010a, b, 2015), our knowledge of ice sheet dynamics over the uplands of the North Pennines remain more generalized (Livingstone et al., 2008, 2012; Evans et al., 2009) or site-specific (Rose 1980; Mitchell, 2007). This forms a significant gap in our knowledge of the BIIS, not just geographically but also conceptually, because the region contains evidence for the former operation of palaeo-ice streams over upland terrains, where ice sheet inundation resulted in regional watershed breaching and interaction with locally based plateau icefields. The glacial geomorphology of the area thereby augments a rich and expanding database on palaeo-ice streams that is otherwise predominantly founded on evidence from lowland settings.

The aim of this paper is to report the glacial geomorphological evidence for the evolution of the BIIS over the northern Pennines, with particular emphasis on Teesdale (Figure 1), because of its location at the suture zone between locally-sourced Pennine plateau ice and regional ice streams driven by the relatively more vigorous full glacial flow of Scottish ice. Details on the style of deglaciation are also proposed based upon systematic mapping of ice-marginal landforms and deposits, thereby identifying north Pennine signatures of potential ice sheet marginal responses to regional climate change at the close of the last glaciation.

2. Previous investigations

The complexity of regional ice flow in Northern England has long been recognised and early attempts to explain complex drumlin orientations, erratic pathways and multiple till stratigraphies, pertaining largely to the Vale of Eden, were reliant upon the now outdated notion of "basal icesheds" (Harmer, 1928; Hollingworth, 1931). The cross-cutting of subglacial bedforms like drumlins was later explained in a way that did not rely upon this physically implausible concept of ice dynamics. Rose and Letzer (1977) described overprinted subglacial bedforms and ascribed them to changing ice flow directions. These changes were driven by migrating ice-dispersal centres, as explained by Mitchell (1991a, b, 1994) and Mitchell and Letzer (2006), who proposed an ice-flow reversal in the Vale of Eden driven by ice-divide migration associated with a Dales Ice Centre located over the western Yorkshire Dales, the Howgill Fells and the Lake District.

The early work of Dakyns et al. (1891), Dwerryhouse (1902) and Raistrick (1931) clearly acknowledged that the north Pennines was an independent ice dispersal centre. They envisaged that the ice built up in the easterly-facing valley heads lying below the Cross Fell-Mickle Fell summit ridge (Figure 1b) and then flowed north and east as valley glaciers in the Tyne, Wear and Tees catchments. Regional (Scottish-sourced) ice then flowed around this partially ice-covered upland, creating major ice streams in the Tyne Gap and Vale of Eden/Stanmore Gap. But rather than inundate the North Pennines, the regional ice was thought to have flowed around nunataks (Dwerryhouse, 1902; Raistrick, 1931), based upon the assumption that the summit blockfields of the area (Tufnell, 1969, 1985; Mitchell and Huddart, 2002) required long periods of freeze-thaw weathering to develop and hence must have lay above the ice during glaciation. An early challenge to this view came from Trotter (1929a), who suggested that the blockfield had survived beneath thin and passive glacier ice; indeed it is now more conventional to interpret the transition between upper drift limits and blockfield as thermal boundaries in ice sheets (e.g. Phillips et al., 2006; Kleman and Glasser, 2007; Ballantyne, 2013; McCarroll, 2016).

The extent of the regional ice and the persistence of plateau-centred local ice, instead of palaeonunataks, throughout glaciation was identified by the mapping of erratics (Johnson and Dunham, 1963; Vincent, 1969; Taylor et al., 1971; Francis, 1970; Lunn, 1995a, b, 2004). This showed that only the higher plateaux of Cross Fell and Cold Fell generated independent ice and that the Cross Fell ice flowed radially but most strongly eastwards down Teesdale (Figure 2). Compelling evidence for an additional northerly flow by Cross Fell ice is manifest in the huge erratic blocks or mega rafts of Great Limestone called the Bullman Hills and Lambgreen Hills, which have been moved between 300 and 900 m from the Cross Fell summit (Lunn, 1995a, b).

More localized complex ice flow patterns during the last glaciation were identified by Mitchell (2007) in the upper Teesdale catchment based on the apparent cross-cutting relationships of the drumlins in the Moor House/Cow Green area. An early southerly ice flow appears to have been driven by an west-east aligned ice divide but this was replaced by an easterly to southeasterly ice flow when the ice divide migrated westwards and re-aligned in a NW-SE trend centred over the main spine of the Cross Fell-Dufton Fell ridge.

Within Teesdale the characteristics of the drift have been reported in detail only by Dwerryhouse (1902) and then later by Mills and Hull (1978). This drift locally thickens to form elongate, streamlined ridges, which Dwerryhouse (1902) interpreted as drumlins, where they lie on the valley floor, or lateral moraines, where they occupy the valley sides. He identified two till types within the drift based upon either red sandy or grey clay matrix. He also documented black loamy clay with few clasts in the tributary valleys to Teesdale which he interpreted as the deposits of ice-dammed lakes created by a valley-based style of glaciation.

Refinements to the early reconstructions of changing ice flows have been made more recently by Livingstone et al. (2008, 2012) and have been numerically modelled by Evans et al. (2009) but the specific details of ice dynamics within the north Pennines remain to be elucidated. Regional ice flow was clearly dominated by the Tyne Gap (Livingstone et al., 2010b) and Stainmore Gap (Livingstone et al., 2008) ice streams and similarly orientated ice flow indicators in Teesdale form part of a regional scale streamlining classified by Livingstone et al. (2008) as flow sets ST1/ST2 (Stainmore ice stream) and ST3 and ST4 (Teesdale ice stream; Figure 3). The Teesdale and Weardale ice streams contributed significantly to easterly flowing regional ice during the last glaciation but were more topographically confined than those of the Tyne Gap and Stainmore Gap, which were closer to pure ice streams in that they were driven more by regional ice sheet driving stresses. The limits of the Teesdale and Weardale ice, or more specifically their suture zones with Tyne Gap and Stainmore Gap ice respectively were first identified by Dwerryhouse (1902) using the distribution of regional erratics. Weardale ice appears to have been deflected as far south as Abbey Burn, 5km south of Consett, based upon the distribution of Scottish sourced granites. Teesdale ice was deflected significantly northwards downstream of Middleton-in-Teesdale to flow into the drainage of the Gaunless Valley (Figure 1b), as determined by the distribution of Shap granites delivered by the Stainmore ice stream. The deflection of both the Weardale and Teesdale ice resulted in them likely becoming tightly constricted flow units within the easterly flowing regional ice that was dominated by the Tyne Gap and Stainmore Gap ice streams (Figure 2).

This general pattern of erratic distribution is reflected in the lithologically-based classifications of the Pennine tills, although little work has been undertaken on their provenance and sedimentology (Aveline and Hughes, 1888; Dakyns et al., 1890a, b, 1891). The most recent nomenclature proposed by McMillan et al. (2011) recognizes: a) the Yorkshire Dales Till Formation, which is a compact diamicton with a lack of facies variability and dominated by local Carboniferous lithologies and hence derived locally from the Pennines; b) the Stainmore Forest Till Formation of the Stainmore Gap, again dominated by local Carboniferous lithologies but also containing Shap granite and Lake District erratics; and c) the Wear Till Formation, with local Carboniferous material and Lake District and Scottish erratics derived from ice passing through the Tyne Gap.

The relationships between the subglacially streamlined features of the Teesdale and the Stainmore Gap ice streams and other glacial landforms have been contextualized by Livingstone et al. (2012). In addition to the streamlined subglacial landforms related to ice flow sets ST1-4, some significant moraines (Feldom, Great Smeaton and Leeming moraines) demarcate stillstands or readvances of valley-based ice during overall recession (Bridgland et al., 2011; Mitchell et al., 2010; Figure 3).

The above review indicates that some significant advances have been made in the reconstruction of regional ice sheet dynamics over Northern England. However, the local details of such reconstructions, particularly over the North Pennines, are less advanced. This is well illustrated by the lack of stratigraphic nomenclature for the north Pennines (Bowen 1999) and patchy detail in the most recent map of glacial landforms of Britain and Ireland in the *BRITICE Glacial Map, version 2* compilation of Clark et al. (2017). Our investigations detailed below attempt to rectify this lack of a systematic and detailed database.

3. Methods

Geomorphological features were mapped through a process of on-screen digitisation of landforms from NEXTMap Britain imagery. NEXTMap is a digital elevation model (DEM) with a 5m spatial resolution derived from airborne interferometric synthetic aperture radar. Using ArcMap GIS software, it is possible to manipulate this imagery to best visualise landforms within the landscape. Smith and Clark (2005) highlight the importance of applying a range of visualisation techniques to DEM imagery to depict subtle variations in topography and account for any visual bias (Smith et al., 2001). To that end, the DEM was artificially lit from both the northeast (045°) and northwest (315°), to produce two separate images that best illuminate all features within the landscape (BonhamCarter, 1994; Onorati et al., 1992). Furthermore, slope gradient was calculated to represent the rate of change in elevation for the DEM, for further visualisation and validation.

At 2m spatial resolution, Light Detecting and Ranging (LiDAR) DEM imagery has a significantly greater resolution than NEXTMap imagery, thus can more easily depict subtle topographic variations within the landscape. Therefore, LiDAR data were used but availability was restricted to the banks of the River

Tees and its main tributaries. The mapped features were exhaustively field checked to reduce ambiguity in description and interpretation (Smith et al. 2006).

Landforms were grouped into thirteen descriptive categories prior to interpretation and are classified on the main map (Supplementary Information Figure 1) according to both descriptive and interpretive nomenclature. This allows the compilation of all geomorphic detail on a single map that combines description and genetic interpretation; explanations for genetic classification and their derivation from descriptive detail are provided in the following sections under six landform categories including: i) bedrock controlled features; ii) discrete mounds and hills; iii) drift mounds; iv) streamlined landforms; v) glacifluvial outwash and depositional ridges; and vi) relict channels and valleys. The landform map is presented as an overlay on the NEXTMap DEM (Supp. Info. Figure 1) in order to facilitate direct comparison between the imagery and the identified features. Important landform assemblages lying immediately beyond the main map area are presented in smaller scale map/DEM illustrations.

Sediments and stratigraphy were analysed wherever suitable exposures were available and are recorded in scaled section sketches and vertical profile logs. These include information on primary sedimentary structures, bed contacts, sediment body geometry, sorting and texture, as well as any pertinent data on clast macrofabric and clast form. These data are then used to characterize lithofacies types and to allocate facies codes following the procedures of Evans and Benn (2004). Clast macrofabrics were measured on samples of 50 clasts from diamictons using A-axis orientation and dips and then plotted as Schmidt equal-area lower hemisphere diagrams in Rockworks. Each sample was then analysed for strength, modality and isotropy following procedures outlined by Benn (1994, 2004a), Hicock et al. (1996) and Evans et al. (2007; see Evans, 2018 for a review). Clast form analysis was undertaken on samples of 50 clasts and involved assessments of Powers roundness and clast shape following procedures outlined by Benn (2004b) and Lukas et al. (2013).

4. Landforms and sediments

4.1 General geology and physiography

The physiography of the northern Pennines, and Teesdale in particular, is dictated by the fabric of the bedrock geology, which gives rise to an eastward dipping dissected plateau, upon which it is thought that early eastward-draining river networks were developed (Mills and Hull, 1976; Figure 4). In the eastern part of the study area, relatively higher terrain (Woodland/Butterknowle upland; Figure 5) composed of Carboniferous Lower Coal Measures forms the upland plateau called Woodland Fell and Langleydale Common as well a prominent south-facing scarp located along the lines of the Butterknowle, Copley and Wigglesworth faults. To the south of this scarp, the older sandstone and limestone lithologies of the Millstone Grit Series form the relatively lower relief of Marwood and Staindrop Moor (Figure 5). West of Middleton-in-Teesdale, the main valley of Teesdale is aligned along the Teesdale Fault and thereby forms a deep incision into the subhorizontally bedded Carboniferous limestones of the fault bounded Alston Block. The Alston Block forms the highest terrain along the north Pennine hills as well as the abrupt relief of the Pennine Escarpment, located along the contact of the Cross Fell Inlier at the western edge of the study area (Figure 5). This higher terrain includes Cross Fell, the highest point on the Pennine chain at 893m OD and several other tableland-like plateaux (e.g. Mickle Fell, Meldon Hill and Stainmore Common) that form the upland topography in the west of the study area.

The landforms of the northern Pennines also commonly display a strong inheritance of the underlying bedrock. For example, sub-horizontal valley-side benches and flat-topped mountain summits or mesas and buttes reflect the flat-lying to shallow dipping strata of the Carboniferous sandstones, millstone grits, limestones and coal measures over most of the region (Mills and Hull, 1976). Quaternary deposits that overlie this stepped bedrock topography thicken in valley bottoms in a range of glacial landforms but thin rapidly upslope above the middle Tees valley and its tributaries to form a clear drift limit; above this limit the Quaternary deposits form an often patchy veneer through which bedrock structure is clearly visible. Mapped over the region as "boulder clay" with valley floor pockets of "glacial sand and gravel" (Mills and Hull, 1976), this Quaternary cover thins also towards the valley heads of upper Teesdale, Lunedale, Baldersdale and Deepdale. The north Pennine mountain chain (600-890 m OD) is punctuated by passes to the north and south of the Mickle Fell/Little Fell summit ridge, the latter forming one of several cols that feed into the drainage basins of Lunedale, Baldersdale and Deepdale. Together these valleys form a streamlined, relatively lower elevation topography collectively named the Stainmore Gap, after the pass (Stainmore Common/Cotherstone Moor) that crosses the North Pennines between the higher summit massifs of the Durham and Yorkshire dales (Figure 5).

4.2 Bedrock controlled features

4.2.1 Description

The well-developed frost shattered summit bedrock or blockfield that occurs on Cross Fell (Mitchell and Huddart, 2002) and adjacent hilltops is central to long standing debates on the former existence of nunataks above the BIIS (Dwerryhouse, 1902; Raistrick, 1931; see Evans, 2016 for a review). Small areas of blockfield exist on the summits of Little Fell, Mickle Fell, Long Crag and Bink Moss to the south of the River Tees, and Middleton Common, Monk's Moor and Eggleston Common to the north (Figure 1b & Supp. Info. Figure 1). The alternative interpretation of these proposed palaeonunataks as being areas that were ice covered but lying above the transition zone between high altitude cold based and lower altitude warm-based ice is now more widely preferred (Trotter, 1929a; Phillips et al., 2006; Kleman and Glasser, 2007; Ballantyne, 2013; McCarroll, 2016).

Small areas of rock slope failure have been identified in the study area in order to determine the pattern of unequivocal glacially-influenced landforms (Supp. Info. Figure 1). Two large areas of ridged and hummocky terrain occur on the northeast slopes of Herdship Fell, the northernmost of which having been mapped previously by Mitchell (2007). They have the appearance of rockslides and extensional rock slope deformations (Jarman, 2006) in which elongate slabs of the horizontal bedrock strata have foundered short distances down slope. Elsewhere, rock slope failures are only minor landform features but two examples are mapped on the eastern slopes of Monk's Moor and on the south slope of Helbeck Fell. Clearly the bedrock of the study area is prone to rock slope failure, likely more so as detachment slides in permafrost, as well as glacitectonic rafting, and hence the evolution of discrete mounds and hills (see below) could be related to a combination of such processes; indeed the Bullman and Lambgreen hills north of Cross Fell have been related to both sets of processes (Evans, 2017).

The importance of bedrock dislocation and glacitectonic raft development in the Carboniferous strata of the study area has been demonstrated by Mills (1976), based upon sub-surface structures in opencast coal mines near Tow Law, and by Lunn (1995a, b) based upon landforms as exemplified by the Bullman Hills and Lambgreen Hills to the north of Cross Fell (Figure 6). Although these case studies lie just outside the map area, they are pertinent here with respect to the glacial evolution of landforms and sediments in this study and therefore are now briefly reviewed.

Localized hillocks around the area of the Sunniside interfluve at Broom Hill, near Tow Law were traditionally regarded as sandstone outliers overlying the Coal Measures, but were found to be glacitectonic bedrock rafts once they were excavated (Mills, 1976; Figure 6a). The largest, the Broom Hill raft, is 3 hectares in area and 12 m thick and has been lifted 45 m upslope over a distance of less than 1 km. It comprises largely undisturbed Coal Measures, specifically the Top and Bottom Busty seams, which have been displaced to form a repeat vertical stratigraphy separated by □ 3 m of till and capped by a thin till carapace. A further smaller raft (Dicken House Lane raft) has been displaced vertically by up to 36 m. Conducive to raft production here is the cyclic nature of the bedding and the concomitant juxtaposition of relatively competent and incompetent strata, with argillaceous fireclays acting as effective aquicludes and thereby concentrating subglacial porewater pressures at the boundaries with overlying strata and initiating decollement.

Less is known about the characteristics of the Bullman and Lambgreen hills rafts north of Cross Fell (Figure 6b), although Lunn (1995a, b) has proposed that they were glacially transported a short distance northwards from their source location at the edge of the Cross Fell summit plateau; if correct, they constitute evidence of a plateau-centred, radially flowing ice dispersal centre. The erratic nature of the Bullman and Lambgreen hills is acknowledged on British Geological Survey maps where they are mapped as landslips. The hills are therefore false mesas/buttes comprising relatively undisturbed Great Limestone strata, suggesting that their transport distance was short. Like the Tow Law rafts, the Bullman and Lambgreen hills rafts were likely displaced over marine beds (mudstones) within the bedrock stratigraphy but their initial position at the summit of Cross Fell would have facilitated both detachment sliding in a permafrost setting (i.e. a landslip origin) and dislocation by glacier ice that would been thin and frozen to its substrate at this high altitude; clearly a hybrid origin is distinctly possible (Evans, 2017).

Due to the sub-horizontal layering of the bedrock strata of the region, in addition to the tablelandlike larger plateaux, a number of prominent mesas or buttes occur on the skylines of the upland areas. These are well developed on Cotherstone Moor and include Goldsborough, Shacklesborough, Sun Dodd and Ravock. Each of these large tabular bedrock mounds has been partially streamlined, with the orientation of the streamlining being parallel to that of surrounding drumlins and lineations (see below). For example, the prominent tabular bedrock summit of Goldsborough appears to be associated with two down-ice tails (Figure 7), and the outline of Ravock appears asymmetrical, with a streamlined west-facing nose and a linear east-facing scarp; conspicuous immediately east of the scarp is an extensive area of densely spaced and unevenly-sized conical hummocks. Similar assemblages of hummocks are the Burners Hills, located immediately to the west of Goldsborough, and the Knotts Hills, which lie on the shoulder of a streamlined ridge to the south of Burners Hills (Figure 7). Directly to the south and located on the southern slopes of the Stainmore Gap, above the village of Bowes, lie the prominent hummocks of the Seven Hills, which appear to be composed entirely of highly disaggregated local limestone blocks. These landforms comprise sharp relief mounds that are closely spaced but isolated (Figure 8) and hence do not resemble normal hummocky moraine spreads. They also lie on the summits of relatively high terrain, rather than in valleys, where tills are thin and discontinuous. Exposures through the various “Hills” of the study area are rare but they are described as bedrock controlled features rather than moraines due to their Limestone or sandstone block composition. Importantly, the Burners Hills, like the Great Limestone blocks of the Bulman and Lambgreen Hills, appear to lie directly over thick mudstone strata, as demonstrated by an exposure in an adjacent river cliff (Figure 9). The mudstone here displays an upper 1-2 m thick crushed zone characterized by densely spaced anastomosing partings or prominent fissility. This zone is capped by

<2 m of mudstone-rich, matrix-supported diamicton that likely represents the local till. The nearby outcrop of Goldsborough demonstrates that a formerly more expansive cover of sandstone once capped the mudstone but is now only locally preserved in remnant mesas.

4.2.2 Interpretation

For the bedrock controlled features not previously ascribed a genesis, a glacitectonic rafting origin appears the most likely explanation. The asymmetrical shaped mesa called Ravock and its down valley assemblage of densely spaced and unevenly-sized hummocks resembles a giant roche moutonnée (cf. Sugden et al., 1992) with a downflow tail of blocks plucked from its east-facing quarried face (scarp; Supp. Info. Figure 1 & Figure 7). Similarly, the horseshore-shaped plan form of Goldsborough strongly resembles that of the horned crag-and-tails reported by Jansson and Kleman (1999; Figure 7). The Burners Hills and Knotts Hills are also conspicuous and appear to be assemblages of blocks and are potentially the products of completely disaggregated mesas. The Seven Hills, although morainic in appearance, also appear to be composed entirely of disaggregated limestone blocks and hence have been quarried from nearby bedrock outcrops. Given the propensity for the local bedrock to glacitectonic rafting, as demonstrated by the Toft Hill and Bullman/Lambgreen hills case studies reviewed above, it is perhaps not surprising to find evidence of such megascale glacial erosion. If the fields of unevenly-sized hummocks are morainic in origin, their locations on hill summits, often closely associated with mesas or buttes, and the occurrence of bedrock cores, require explanation. A similar type of terrain has been identified on the Canadian prairies, where it often lies down ice from depressions formed by the excavation of bedrock slabs. This has been termed 'rubble moraine' by Fenton (1987) and Aber et al. (1989) and documents the short transport distances and surface expression of bedrock megablocks or rafts. The juxtapositions of the Goldsborough mesa and the Burners Hills and Ravock and its down valley assemblage of hummocks suggest that the mesa remnants of formerly more expansive covers of sandstone could conceivably seed glacitectonic rafts. Sandstone and/or limestone blocks at mesa edges could be plucked as a response to their coupling with overriding ice and then displaced along a decollement plane at the junction with underlying mudstones, thereby creating intense glacitectonized or shear zones, evidenced by the fissile upper mudstone horizons capped by till. Hence a glacitectonized raft cluster hypothesis (rubble moraine) is proposed for the Burners, Knotts and Seven hills assemblages. The north-south alignment of the Burners, Knotts and Seven Hills and their proximity to the Ravock plucked blocks and the Tute Hill moraine (see drift mounds), potentially demarcates an ice sheet marginal readvance position. If this is the case then it is apparent that the sub-marginal to marginal processes involved in moraine construction were capable of plucking substantial volumes of bedrock and that till layers were discontinuous or even patchy. Frozen snout conditions of the type associated with the development of a polythermal regime in this relatively high altitude setting would be a likely trigger for such substrate excavation (Bennett et al., 1999), especially where limestone lies directly over mudstone, as illustrated by the Bullman and Lambgreen Hills (Lunn, 1995a, b; Evans, 2017) as well as the Burners Hills. Considering these indications that the bedrock strata of the Northern Pennines are susceptible to glacitectonic raft liberation and transport, there is a strong possibility that numerous examples of the 'discrete mounds and hills' may also be buried megablocks/rafts or examples of 'rubble moraine'. Hence, potential bedrock controls are discussed below in relation to the description and glacial interpretations of discrete mounds and hills. **4.3 Discrete mounds and hills (streamlining possible)**

4.3.1 Description

The term 'discrete' is employed here to refer to features that appear significant in terms of landscape evolution because they are unlike the regular surface undulations that are clearly controlled by underlying lithology and structure. Their distribution and pattern on the landscape are also unlike those created by localized rock slope failures and instead appear as large scale hummocky terrain with only rare and localized indications of faint streamlining (Supp. Info. Figure 1). A general lack of exposures through many such features hinders their classification according to their component materials, especially as the 'boulder clay' that has been mapped in areas of their occurrence may appear either as glacigenic diamictons or (glacitectonized) bedrock. Because genetic terminology often initiates confusion, especially if it is employed based upon morphology alone, we follow the recommendation of Whalley (2009, 2012; i.e. 'discrete debris accumulation') in the use of the non-genetic term 'discrete' when referring to conspicuous landforms of largely unknown component materials; alternative interpretive scenarios are then proposed based upon the range of possible components. These features occur in two main areas in Teesdale, specifically in the Cow Green Reservoir/Moorhouse area and in a broad arc located east of Barnard Castle (Supp. Info. Figure 1). Some of these mounds display subtle evidence of streamlining and indeed the Cow Green Reservoir examples appear to be drift-cored and have been interpreted as superimposed drumlins by Mitchell (2007). Additionally, some mounds and hills lie amongst streamlined landforms and thereby likely form part of a continuum of smoothed features (cf. Rose 1987; Ely et al. 2016).

The discrete mounds of the Cow Green Reservoir/Moorhouse area (Figure 11a) are referred to as the 'upper Tees drumlin field' by Mitchell (2007), who proposes that 134 individuals are visible, 12 of which are superimposed (cf. Rose & Letzer 1977; Clark 1993). A mean elongation ratio of 2.2 indicates that the mounds are not very streamlined but do indicate an overall easterly ice flow direction (Figure 10). This low elongation is in contrast to the majority of the streamlined landforms of the study area and hence their inclusion in this section as discrete mounds and hills. Based upon the superimposed forms, Mitchell (2007) proposes that an early southerly and southeasterly ice flow direction was replaced by a more vigorous easterly ice flow, thereby documenting a change in ice dispersal from an early northerly ice divide to a later westerly ice divide. This ice dispersal centre was localized (i.e. centred on the Cross Fell summit chain) and, based upon the distribution of local Pennine versus regional Lake District erratics (Johnson and Dunham, 1963; Vincent, 1969; Taylor et al., 1971; Lunn, 1995a, b), is thought to have resisted overriding by the regional ice sheet flow (Figure 2). The sediments of the upper Tees drumlins range from massive, matrix-supported diamict to clast-rich or gravelly diamicts with extensive beds of cobble to boulder gravel. The exposures on the eastern side of Cow Green Reservoir lie within the zone of overprinted drumlins proposed by Mitchell (2007) and hence could contain evidence of multiple ice flow directions if the enclosed diamictons are subglacial tills and their clast macrofabric signatures indicate vertical accretion beneath dynamic ice. In order to test this, a vertical sequence of clast macrofabrics was obtained from a 2.5 m high exposure through massive, matrix-supported diamicton, containing clasts with typical subglacially abraded forms and striations, and overlying striated bedrock. Macrofabric strengths are only moderate (Figure 11b) but the lower and upper samples display orientations indicative of stress induced from the NNW. The middle macrofabric is the weaker of the three and displays a more northerly orientation indicative of a north-south directed stress. A weakly WSW dipping clast macrofabric was obtained from a lower diamicton in a drumlinized mound at Dubbysike, at the western end of Cow Green Reservoir.

The broad, down-valley convex arcuate zone of discrete mounds east of Barnard Castle, hereby named the 'Humbleton mound belt' (HMB), can be differentiated based upon its abrupt western and eastern boundaries with strongly streamlined terrain. Some streamlining is evident within the HMB but it is characterized more by largely non-orientated mounds of varying size and shape (10-30 m relief), some of which appear to form arcuate linear chains accentuated by the incision of intervening relict channels but which nonetheless also appear down-valley concave in plan form (Figure 12). Streamlining across the mounds appears to be a continuation of that recorded by the elongate streamlined landforms on either side of the HMB; the orientations of the long axes of these landforms is strongly west to east but fanning out to cross-cut the linearity in the mound patterns at right angles. At its southern limit, the HMB curves sharply westwards to occupy the watershed between the River Tees and Skeeby Beck, effectively blocking the former southeasterly route of the Tees when it was a tributary of the River Swale (see below), a valley now occupied by Skeeby Beck. At this southwestern end of the HMB the mounds give way to inset moraine ridges and meltwater channels developed on the north-facing slopes of Scargill High Moor and Barningham Moor (see below), including the Feldom Moraine of Kendall and Wroot (1924), Raistrick (1926, 1932) and Wells (1955). The streamlining in the Tees valley at this location also locally fans out to turn southeastwards to meet the HMB linearity.

There are no large exposures through the HMB but the higher mounds such as Humbleton Hill and East Whorley Hill are mapped by the BGS as outliers of Stainmore Formation Mudstone with a till carapace. Exposures afforded by cuttings in the abandoned railway grade in Broomielaw channel (see section 4.7) reveal that thick sequences of this till occupy the lower topography of the HMB. At the northwesternmost edge of the HMB, at High Shipley, quarrying has exposed bedrock at the ground surface (Figure 13) which is fractured and deformed and in the early stages of crushing. An important landform comprising rectilinear scarps arranged in a linked series of right angles occurs in the vicinity of Westwick Moor (Figure 14); as no human made super quarries have ever operated here, these scarps must document large scale bedrock removal by natural causes. Also located in this vicinity and extending from here eastwards is a sinuous ridge, thought likely to be an esker due to its marked morphological difference to the larger discrete mounds of the HMB (Figure 14), although no exposures are available to verify this interpretation.

Predominantly chaotic, low relief drift mounds occur on the floor of the Langleydale channel, at the northern edge of the HMB. Significant incision has taken place here due to late stage meltwater erosion but an overall sense of west-east aligned streamlining is apparent. This drift infill is significant in terms of the long timescale development of Langleydale and hence is discussed further in section 4.7.

Some discrete mounds and hills appear to be more linear or curvilinear in plan form, an excellent example being those on the floor of Harwood Beck, which were interpreted as drumlinoid drift tails by Mitchell (2007) but clearly link to some substantial cross-valley mounds composed of thick diamicton sequences (Figures 10 & 15). Although these ridges appear smoothed, they nevertheless form arcuate assemblages comprising valley-side components, aligned obliquely to the contours and descending down valley. The orientations of the cross valley components are transverse to the former glacier flow indicated by Mitchell's (2007) streamlined drift mounds and discrete lineations (see below), which lie immediately upslope and down-valley of them. However, faint ice flowparallel lineations on their surface indicate that they have been glacially overrun (Supp. Info. Figure 1 & Figure 10). Northeast illumination angles on the DEM in particular highlight sinuous ridges within the drumlins to the west of Herdship Fell (Figure 10), indicating that the drumlinization in this area may not have completely modified earlier linear features.

4.3.2 Interpretation

Discrete mounds that lie amongst streamlined landforms, if they form part of a continuum of smoothed features, are likely to be subglacial in origin even though their cores are of unknown material (cf. Ely et al., 2016). Similar features composed of drift are described as ‘ovoid forms’ by Piotrowski and Vahldiek (1991), who contemplate an overridden moraine origin for such features. The ovoid forms in Teesdale could also be bedrock megablocks/rafts that are non-streamlined but nevertheless covered by a till carapace and hence are examples of ‘rubble moraine’.

More streamlined features, such as those in the Cow Green/Moorhouse area, have been interpreted as superimposed drumlins with low elongation ratios (Mitchell, 2007). Certainly the matrixsupported diamictons with moderate macrofabric strengths on the east side of Cow Green Reservoir are compatible with known subglacial tills and if subglacial in origin they record ice flow towards the SSE. This flow direction was likely topographically controlled by the upland area of Widdybank Fell, which would have forced the basal glacier ice moving down the upper Tees valley to flow southwards towards Cauldron Snout. Because this is topographically constrained ice flow, it likely relates to a phase of more restricted glacier coverage; full glacial (ice sheet) coverage forced ice flow directly over Widdybank Fell as recorded in the W-E aligned streamlined topography over the higher terrain and into Harwood Beck. Whether or not these clast macrofabrics record Mitchell’s (2007) early phase of drumlin formation is unclear. Evidence of a WSW-ENE ice flow is recorded in a lower till clast macrofabric at Dubbysike, in a drumlinized mound at the western end of Cow Green Reservoir but its stratigraphic correlation to the macrofabrics below Widdybank Fell is difficult to ascertain.
The arcuate assemblages of drift mounds on the lower valley sides and floor of Harwood Beck strongly resemble latero-frontal moraines. They appear to have been glacially overrun (Mitchell, 2007) but their form and location strongly suggests that these landforms originated as moraines. The sinuous ridges within the drumlins to the west of Herdship Fell are likely an up-valley continuation of a series of such moraines.

Key to unravelling the likely origins of the HMB are the Westwick Moor rectilinear scarps. The only process that could be effective in removing the bedrock blocks from these rectilinear scarps is large scale glacitectonic raft displacement or mega-plucking from stepped bedrock profiles (e.g. Krabbendam and Bradwell, 2011), but the location of the displaced blocks is not immediately obvious. The unusually high relief of mounds like Humbleton Hill and East Whorley Hill could be the products of glacitectonic raft displacement from such source hollows, an hypothesis that can be tested only by the creation of large exposures or the extraction of borehole data from the HMB. However, the arcuate plan form of the HMB depicted at the smallest scale of mapping (Figure 12), orientated transverse to former regional ice flow, strongly suggests that it demarcates the margin of a glacier lobe that formerly flowed across the Stainmore Gap. The mounds were created when ice later flowed over them, streamlining their forms and creating a large scale example of what is best described as “rubble terrain” rather than rubble moraine. Hence it is proposed that the HMB is an overridden moraine belt. Although thick till appears to have been deposited in the channels that cut through the HMB (e.g. Broomielaw channel), till cover is discontinuous, as illustrated by the High Shipley quarry exposure through near surface fractured and crushed bedrock, a material that likely represents immature bedrock glacitectonite production (*sensu* Heimstra et al., 2007).

4.4 Drift mounds and ridges (non-streamlined)

4.4.1 Description

Smaller scale and sharper relief (non-streamlined) drift mounds appear as largely linear, hummocky ridges and ridge complexes. A number of these have previously been interpreted as moraines and hence are described as such in this section.

On the Woodland/Butterknowle upland, above the Langleydale and Gaunless channels, drift ridges largely parallel the bedrock-controlled linear grain (Supp. Info. Figure 1). The subtle differences between the drift mounds and the similarly orientated bedrock structure in this area are best exemplified by the crests of Penny Hill and Crag Top (Figure 16). Exposures reveal diamictons (locally classified as tills by Mills and Hull, 1976) rich in local bedrock clasts and rafts. These characteristics indicate that ridge construction was strongly linked to, or facilitated by, the exploitation of bedrock structure. Further east in the area around Staindrop, Cockfield, Evenwood and West Auckland, a 'belt of thick locally hummocky drift' (till thicknesses □ 16.5 m) has been mapped by Mills and Hull (1976) and constitutes the thickening and widening of the glacigenic deposits and landforms from the upper to middle reaches of the River Gaunless catchment (Supp. Info. Figure 1). It can be traced to a series of linear hummocky tracts of drift in the area around Gibbsneese, thereby forming a 10 km long partially lobate assemblage. To the north, drift again appears to be arranged in a series of west-east aligned hummocky ridges. Some mounds in this area are identified as glacifluvial sand and gravel by Mills and Hull (1976), including a significant landform locally named Woolly Hills (see section 4.6). The morainic origin of some of these ridges is highly likely where they comprise till, for example at Cowley where a prominent ridge coincides with borehole evidence of 14 m of 'boulder clay' (Mills and Hull, 1976).

An inset series of ridges and associated relict channels occur on the north-facing slopes of Scargill High Moor and Barningham Moor, to the south of the study area (Figure 12). One of these ridges has been previously classified as the Feldom Moraine (Figure 3) by Kendall and Wroot (1924), Raistrick (1926, 1932) and Wells (1955; see Bridgland et al., 2011 for a review of the glacial geomorphology of this area). Immediately to the west, a narrow and low amplitude drift ridge, comprising bouldery diamicton, straddles the interfluve of Tute Hill, in the centre of Stainmore (Figures 7 & 17). This feature trends obliquely to the streamlined landforms of Stainmore and lies in the vicinity of the conical hummock terrain at Ravock, the Seven Hills and the Knotts Hills.

A substantial assemblage of drift mounds forms an arcuate loop across the main Teesdale valley between the villages of Romaldkirk and Cotherstone, the largest of which is a wide cross-valley ridge, named locally the Gueswick Hills and mapped as morainic drift by Mills and Hull (1976; Figures 18 & 19). The Gueswick Hills can be traced onto the west and east slopes of Teesdale as discontinuous linear ridges; those on the northeast slopes below High Shipley ascend diagonally upslope to a more extensive assemblage of mounds in the area around Folly Head and Windy Hill and those on the southwest bank form an arc that extends up stream to join patchy drift mounds around Romaldkirk (Figure 18). A further series of inset linear drift ridges and associated relict channels diagonally ascend the southwest valley slopes (Romaldkirk Moor/Bail Hill) into Lunedale. Relict channels have been excavated through, and east of, the Folly Head/Windy Hill ridges and around the outer slopes of the Romaldkirk/Gueswick Hills ridges. A further arcuate ridge (Mill Hill) and associated relict channels occurs downstream of the Gueswick Hills, on the northeast bank of the River Tees.

Immediately to the northwest of the Gueswick Hills, a number of discrete, non-streamlined drift mounds and ridges cross local valley sides and interfluves and valley floors. The largest of these mounds are in Eggleston Burn and include a dissected cross valley ridge and an expanse of hummocks and ridges on the interfluve with the main Teesdale valley above Froggerthwaite (Figure 18), the latter interpreted as 'ablation moraine' by Mills and Hull (1976).

An area of substantial drift mounds occurs around the area of Lonton and Laithkirk, at the junction of Lunedale and Teesdale (Figure 18). These features are closely associated with densely spaced and deeply incised relict channels (see section 4.7). The Teesdale channels align with the highest altitude of the drift ridges, which both descend diagonally down slope on the north side of Moor Rigg towards Lonton; Moor Rigg is the interfluve that separates the Teesdale and Lunedale valleys. At Lonton and Laithkirk the drift increases in thickness significantly and forms a wide arc that trends across Teesdale. At its highest point this cross-valley ridge, which has been heavily dissected likely by glacial meltwater and the early postglacial River Tees, indicates a drift thickness of 20 m.

Finally, some prominent valley-side ridges occupy the middle and lower slopes of Widdy Bank, in upper Teesdale, immediately downstream from Cow Green Reservoir. These features are linear to slightly arcuate in plan form and display down-valley sloping crestlines adorned with scattered boulders.

4.4.2 Interpretation

The large, partially lobate expanse of hummocky drift extending from Gibbsneese to Evenwood and West Auckland is most likely morainic in origin, as proposed by Mills and Hull (1976) and hence is hereby called the 'Cockfield Moraine'. This abuts and cross cuts drumlins recording former Stainmore ice flow towards the northeast (Supp. Info. Figure 1). This assemblage appears to demarcate an ice lobe in the middle Gaunless Valley and contains predominantly local materials but also some far-travelled (Lake District) lithologies and hence likely represents the southernmost extension of the Teesdale ice margin in its early stages of decoupling from the Stainmore ice lying over the Staindrop area; at this stage the suture zone glacifluvial assemblage on the Woodland/Butterknowle upland (see section 4.6) had emerged through the downwasting ice sheet surface and the Teesdale ice had become topographically confined within the Gaunless valley, as it migrated southwards due to the diminishing strength of Stainmore ice flow. The smaller ridges that form the crests of Penny Hill and Crag Top are the eastward continuations of the Cockfield Moraine (Supp. Info. Figure 1 & Figure 16). The series of west-east aligned hummocky ridges located to the north do contain some glacifluvial landforms (e.g. Woolly Hills; see section 4.6) but generally represent a morainic assemblage based upon Mills & Hull's (1976) report of thick (14 m) of 'boulder clay'; hence this assemblage is hereby termed the Butterknowle-Woodland Moraine Belt (BWMB).

The general pattern of moraine and glacifluvial landform distribution over the Woodland/Butterknowle upland and nearby Langleydale demarcates the downwasting and westerly recession of trunk ice flowing west to east across Stainmore, the subglacial bedforms of which fill the lower elevation terrain south of the moraines and over the HMB east of Barnard Castle. Although a strong bedrock lithological control over moraine ridge orientation is apparent, this may not be exclusively controlling the elongate pattern of these landforms. Given their location, they likely reflect the concentration of glacigenic depositional processes at the uncoupling margins of the Stainmore and Teesdale ice flow units. The northernmost extent of the suture zone of these two flow units in the region has been mapped by Dwerryhouse (1902) using the distribution of regional till with its diagnostic Lake District erratics. This crosses Teesdale immediately west of Middleton-inTeesdale and extends first eastwards across Eggleston Common and then east-northeastwards along the northern drainage divide of the Gaunless Valley (Supp. Info. Figure 1). The concentration of glacifluvial deposits also at this suture zone is discussed in section 4.6.

The ridges and relict channels on the north-facing slopes of Scargill High Moor and Barningham Moor (including Kendall and Wroot's (1924) Feldom Moraine) are interpreted by Bridgland et al. (2011) as lateral moraines and marginal meltwater channels. They appear to be unaffected by, and hence developed after, the regional terrain streamlining, to which they are orientated sub-parallel. They record a north-northeastward receding ice margin, most likely the snout of topographically constrained ice in Teesdale after the regional west-east flow across Stainmore had shutdown. The lowest elevation examples of the moraine ridges form a multiple ridged arc that lies across the TeesGilling Beck/Skeeby Beck watershed around Ravensworth and West Layton. Postglacial blockage of the proto-Tees drainage at this location and its subsequent diversion into its present easterly orientated channel was proposed by Mills and Hull (1976), who envisaged stagnating ice or a 'minor isostatic upwarp' as the cause rather than a moraine dam. Continued westward recession by Stainmore ice is recorded by the narrow and low amplitude drift ridge at Tute Hill, which due to its cross valley orientation and bouldery diamicton composition is interpreted as a readvance moraine, possibly of the same age as the rubble moraine of the Burners, Knotts and Seven Hills.

The later stages of valley-based ice recession in Teesdale are recorded by a series of moraine arcs west of Barnard Castle. The arcuate loop of drift ridges that crosses the main Teesdale valley and includes the Gueswick Hills is interpreted as a latero-frontal moraine, following the classification of Mills and Hull (1976), and is hereby named the Gueswick Moraine. The associated relict channels, because they parallel the main ridges, are interpreted as lateral meltwater channels. A similar genesis is proposed for the arcuate ridge and associated channels downstream of the Gueswick Hills, especially as they are associated with glacifluvial outwash, and are hereby termed the Mill Hill Moraine (Mills & Hull 1976). Both the Mill Hill and Gueswick frontal moraines can be linked to right lateral moraines that ascend the slopes of Romaldkirk Moor/Bail Hill and left lateral moraines that ascend the slopes of Folly Head/Windy Hill. The drift mounds and ridges located northwest of the Gueswick Moraine are similarly interpreted as glacier marginal deposits. Although exposures are rare, the occurrence of these mounds on valley sides and interfluves and across valley floors strongly suggests that they are glacigenic. The orientation of the expanse of hummocks and ridges above Froggerthwaite, as well as their association with relict channels that can be explained only as lateral meltwater channels relating to an ice margin in Teesdale (see section 4.7), suggests that they originated as a moraine (cf. Mills & Hull 1976) and hence are hereby termed the Froggerthwaite Moraine. This was deposited at the margin of topographically confined ice in Teesdale when it backfilled Eggleshope Valley during overall ice sheet recession. Further ridges in lower Eggleshope Valley and around the village of Eggleston likely record the recession of this ice margin. The drift mounds around Lonton and Laithkirk, together with their closely associated relict channels (see section 4.7), demarcate the receding margins of Teesdale and Lunedale ice. As the mounds occur on the Teesdale side of Moor Rigg they are interpreted as the right latero-frontal moraine of the former Teesdale valley glacier, deposited during its later stages of recession and hereby named the Lonton Moraine. Finally, the most recent of the Teesdale valley glacier moraines occurs below Widdy Bank, in the form of the linear, valley-side ridges, which are interpreted as lateral moraines due to their downvalley sloping crestlines and surface boulders.

4.5 Streamlined landforms (drift mounds and discrete lineations)

4.5.1 Description

Immediately obvious on the digital elevation model is a prominent streamlining of the floors of Teesdale, the Stainmore Gap and the associated Lunedale and Baldersdale valleys (Supp. Info. Figure 1 & Figure 5). This contains substantial streamlined drift mounds (drumlins) as well as more subtle drift lineations and drumlinoid drift tails emanating from interfluves (cf. Mitchell, 2007; Figure 10). Additionally, many streamlined features constitute discrete lineations that are controlled by underlying bedrock structure or grain, especially on the northern slopes of upper Teesdale and on the higher terrain of the Stainmore Gap, similar to those reported for the Tyne Gap palaeo-ice stream bed (Livingstone et al., 2010b, 2015; Krabbendam and Bradwell, 2011). The high col between Mickle Fell and Little Fell appears to have been heavily modified by the streamlining. Here the two blockfield-covered summits are separated by a narrow corridor of NW-SE aligned lineations relating to regional Stainmore ice stream flow. However, the underlying bedrock grain is still visible through the lineations as lithologically controlled steps that can be traced between the two summits but have been modified in the col to appear as discrete mounds (Figure 20).
The streamlined landforms of the study area (locally named drumlins) display some relatively high elongation ratios (□13.75) and a relief of up to 20 m. The most substantial of these lie directly east of Barnard Castle, the largest of which has a relief of 15 m and is 2.75 km long (Figure 12). The streamlined landforms within Teesdale display a clear down-valley trend of increasing elongation, with elongation ratios ranging from 1.73 in the area around Langdon Beck to 13.75 around Barnard Castle (Figures 5, 10 & 12).

Abnormally large streamlined mounds (15-20 m relief) with low elongation ratios (2.25 - 3.0) occur on the floor of upper Teesdale, at Holwick (Figure 21). They are located where drift thickness increases abruptly below the near surface outcrop of the Whin Sill. These elongation ratios and heights are consistent with median values for drumlins globally (Spagnolo et al., 2012; Ely et al., 2016) but the elongation ratios contrast with those of the more spindle-shaped features on the surrounding valley slopes (Supp. Info. Figure 1 & Figure 6), which range from 3.95-6.26 and hence are anomalously low with respect to their down-valley location.

A restricted number of exposures in the streamlined landforms occur in valley floor settings and reveal multiple diamicton sequences up to 10 m thick. This is best exemplified by an exposure at Stack Holme on the floor of Lunedale, part of the Stainmore Gap streamlined landform assemblage.
The landform ridge crest is aligned 276˚- 096˚ indicating a dominant streamlining by the Stainmore Ice Stream (Livingstone et al., 2008) from 276˚. The stratigraphy comprises three diamictons, all similar in terms of their clay-rich matrixes but distinguishable through variable clast content, bounding stratified interbeds and clast macrofabrics (Figure 22). The macrofabrics, measured on both clast A-axes and A/B planes, reveal shapes indicative of girdles to weak clusters and are mostly typical of the type of A-horizon or upper units observed in modern Icelandic subglacial tills (e.g. Benn, 1995; Benn and Evans, 1996; Evans et al., 2016; Figure 22a). The girdle-like nature of most samples renders mean lineation azimuths (MLAs) less useful as stress indicators, due to very low dip angles, but it is assumed that an east to west induced stress direction by glacier ice is untenable and hence westerly orientated MLAs are employed below to assess imposed stress. Clast form data are typical of mature glacigenic modification or long transport distances (Figure 22b) but also show relatively elevated C40 values indicative of less blocky shapes than would normally be seen in subglacial tills. This likely reflects the naturally slabby character of the sedimentary rocks of the local area and hence a tendency to resist

the development of the more blocky end-products typical of long subglacial residence times (Benn and Ballantyne, 1994; Lukas et al., 2013). The lower diamicton is grey, massive and matrix-supported and is separated from the middle diamicton by a laterally extensive stratified interbed comprising fine sand, silt and clay rhythmites. Although they are still sub-horizontal and therefore *in situ*, the rhythmites display clear deformation in the form of intense folding and thrust faults dipping westwards. Both A-axis and A/B plane clast macrofabrics from two samples at the western and eastern ends of the exposure are consistently aligned west-east with MLAs of 260-263˚, indicative of stress from that direction. An A-axis macrofabric from the base of the middle diamicton displays a northwesterly alignment with an MLA of 302˚, recording a shift in the principle stress direction since the emplacement of the underlying diamicton and rhythmites. Clast macrofabrics from the top of the middle diamicton reveal a further shift in stress direction with 242-062° (A-axes) and 244-064° (A/B plane) alignments. The upper diamicton is red-brown coloured, massive and matrix-supported and is notable for its larger concentration of clasts. Clast macrofabrics from its lower part display MLAs of 208° (A-axes) and 215° (A/B planes), indicative of stress directions from the southwest. In contrast, the upper part of the upper diamicton displays an A-axis clast macrofabric with a strong girdle pattern but with an MLA of 296°.

4.5.2 Interpretation

At a regional scale, the streamlining pattern is compatible with Livingstone et als. (2008) flow sets ST1/ST2 (Stainmore ice stream) and ST3 and ST4 (Teesdale ice stream) and hence the landforms are subglacial bedforms. Additionally, the streamlining south of Evenwood (Supp. Info. Figure 1), mapped as part of ST3 by Livingstone et al. (2008), appears to be an earlier phase of Stainmore driven ice flow that was superimposed by the arcuate fanning flow recorded over the HMB and hence is more likely to be representative of the regionally less pronounced flowset ST1. The west to east orientated streamlining that fans out to cross-cut the HMB mound crests records substrate drumlinization by Stainmore ice. The fan-shaped pattern of drumlins in combination with the arcuate orientation of the HMB appears to demarcate the lobate margin of an earlier Stainmorenourished glacier lobe (Supp. Info. Figure 1 & 12). The mounds were streamlined as the lobe flowed over them and hence the HMB is interpreted as an overridden moraine belt.

Watershed breaching by subglacial streamlining appears to have been responsible for the creation of the high col between Mickle Fell and Little Fell (Figure 20). The subglacial lineations have only partially modified the bedrock steps that formerly continued between the two summits. Streamlined cols such as this are potential sources of bedrock rafts, where vigorous ice stream flow would be capable of dislocating the capping strata along narrow upland ridges. A sharp cliff at the northern margin of the streamlining, on the southeast slopes of Mickle Fell, is a potential source scar for such a raft, although this hypothesis may be tested only through the analysis of discrete mounds down ice-flow to prove both bedrock cores and their provenance.

In the Stainmore Gap, streamlining of bedrock structure, specifically the sub-horizontally bedded strata, is readily apparent where lineation crests mimic the structural grain. This locally indicates that ice flow was partially topographically constrained within the Stainmore ice stream, for example in Baldersdale and Lunedale, but it is difficult to ascertain, at least based upon cross-cutting relationships, whether or not this constrained flow was during the late stages of ice stream operation. Other localized bedrock controlled streamlining features include horned crag-and-tails (cf. Jansson and Kleman, 1999), such as the partially streamlined mesa of Goldsborough (Figure 7).

The clast form and fabric data from the Stack Holme diamictons are consistent with a subglacial till genesis, specifically undergoing shear that was directed largely valley-parallel and predominantly aligned with the orientation of the host streamlined landform, indicating that it is a drumlin. The west-east directed shear in the lower, middle (base) and upper (top) diamictons (tills) record drumlin-parallel subglacial deformation, which switched to SW-NE directed shear during the emplacement of the middle (top) and upper (base) tills. The deformed rhythmites likely record subglacial canal fills and hence a phase of ice-bed separation and sliding bed conditions (e.g. Eyles et al., 1982; Evans et al., 1995; Boyce and Eyles, 2000) between the emplacement of the lower and middle tills. Hence the Stack Holme drumlin appears to have been emplaced by the accretion of subglacial deforming layer or traction tills (e.g. Eyles et al., 1982; Boulton, 1987; Evans et al., 1995; Boyce and Eyles, 2000). The details of this accretionary build-up of tills at the glacier-bed interface are much debated and range from deforming/sliding bed switching to pervasive deformation of preexisting deposits (Evans, 2018). Importantly, a range of contemporary observations on deforming subglacial till beds indicates that the till forming processes of deformation, ploughing and lodgement (presumably also melt-out) cannot explain the deposition of thick tills (> 2 m) by single accretionary events but rather by the incremental build-up of till layers over time. Exposures such as that at Stack Holme are therefore important archives of former subglacial till forming processes.

Viewed over the whole study area, the streamlining constitutes a spatial mosaic of subglacial bedforms composed of bedrock erosional forms (e.g. whalebacks, rock drumlins, crag and tails) and till-cored drumlins whose distribution was dictated by till continuity (e.g. Eyles and Doughty, 2016; Eyles et al., 2016; Krabbendam et al., 2016). In the North Pennines it appears that till thickens enough to form drumlins by subglacial deformation only in valley floor settings, which is presumably dictated by the concentration of sedimentation processes in such locations, especially during nonglacial conditions. The isolated nature, abnormally large size and anomalously low elongation ratios of the Holwick drumlins suggest that some aspect of their valley floor location is influential in perturbing the down valley trend of subglacial bedform elongation. Such anomalies prove problematic in deriving theories of universal drumlin forming mechanisms, such as the till “instability theory” of Fowler (2000, 2009, 2010), Dunlop et al. (2008), Clark (2010) and Stokes et al. (2011, 2013). This theory advocates that subglacial bedforms arise from the deformation and local thickening of subglacial till or the downward excavation of the streamlined interface right down to the bedrock substrate in situations where till supply is restricted. Hence drumlins are seen as “emergent” features that develop into swarms with recognizable size and shape patterns; anomalies arise where non-till cored drumlins occur and these are regarded as drumlin “clones” by Clark (2010). If the Holwick drumlins are examples of clones *sensu* Clark (2010), their cores must be different to those of the more elongate drumlins that lie on the surrounding valley slopes, but we have no exposures to test this proposal. However, we can speculate that their valley floor position could relate to a former valley glacier margin and that they originally evolved as moraines before being glacially overrun and streamlined. Other valley floor assemblages that accumulated during earlier deglaciations, such as kames and eskers could also become smoothed during later ice overriding and thereby explain elongation anomalies.

4.6 Glacifluvial outwash and depositional ridges

4.6.1 Description

A number of elongate ridges and associated mounds and benches can be confidently ascribed to glacifluvial depositional processes because they are composed of sands and gravels and have been previously mapped as such. For example, Mills and Hull (1976) reported small accumulations that resemble discontinuous esker ridges immediately north of Barnard Castle and around Staindrop and mapped more extensive spreads of glacifluvial deposits in undulatory and weakly pitted benches on the margins of the River Tees valley floor located between Middleton-in-Teesdale and Romaldkirk (Supp. Info. Figure 1 & Figure 18). Two further spreads of glacifluvial outwash were mapped by Mills and Hull (1976) beyond the Gueswick Hills, their apexes emerging from substantial relict channels cut into the lower slopes of the main valley. Exposures through the glacifluvial deposits in the benches near Mickleton, comprise poorly-sorted, boulder to cobble gravels (Figure 23), and at Cuddy's Bank, west of Eggleston Hall, display a sequence of horizontally bedded gravels and sands overlying diamicton (Figure 24). The Cuddy's bank sequence lies within a broad bench lying between 200-215 m OD. A logged section (Figure 24) reveals that this sequence contains three lithofacies associations (LFA 1-3). At the base, LFA 1 comprises up to 3 m of massive, matrix-supported diamicton (Dmm) with clasts predominantly of local carboniferous and Whin Sill material but also some glacial erratic indicators, such as greywacke and porphyry, originating from the either the Lake District or Scotland. Clast forms are highly blocky and display a sub-rounded modal peak with an average roundness of 2.9. An A-axis clast macrofabric on the Dmm reveals a girdle-like distribution with a clear SW-NE orientation and an S1 eigenvalue of 0.51, indicative of weak to moderate clustering. As this deposit relates to the reconstruction of glacier dynamics rather than glacifluvial deposition at this site, these data are used in the later discussion in relation to ice flow history. Overlying LFA 1 is an interlayered sequence of stratified sands and gravels (LFAs 2 & 3). Planar and trough cross-stratified, massive and locally laminated and rippled sands form LFA2 and massive to matrix-supported gravels constitute LFA3.

A number of discontinuous, elongate and locally sinuous ridges occur within the glacifluvial benches, as well as further up valley, where they lie in isolation on the River Tees floodplain between Middleton-in-Teesdale and Bowlees (Supp. Info. Figure 1). The internal sediments of the ridges near Romaldkirk are exposed in small pits at Hayberries (Figure 25) and are reported in detail by Evans and Phillips (in prep.). The uppermost sediments in the stratigraphic sequence here are gravels and sands typical of glacifluvial sedimentation but the lower sediments comprise a coarsening-upward sequence of clays, silts and sands arranged in rhythmites and include lonestones, typical of deep and quiet water environments, and also display normal faulting. The rhythmites grade upwards into sands and gravels, and in places the gravels appear to form clinoforms or micro-foresets typical of transverse fluvial bars. Deformation structures are well developed in the gravels and sands and comprise shallow thrust faults and fold structures displaying an overall direction of displacement from NW-SE; this displacement is predominantly minor and in the range of only a few meters at most but reveals rafts of stratified sediment (Figure 25b). The uppermost gravels and sands occupy a deep scour in the rhythmites and deformed sands and gravels (Figure 25b). Importantly, they are also interbedded with two massive and matrix-supported diamictons. This complex scour infill, to a depth of 3 m, provides critical information on the deposition of the sinuous ridge at the site. The lowest diamicton in this sequence is a 30 cm thick massive, matrix- supported diamicton (Dmm) with diagnostic subglacial clast forms and an A-axis clast macrofabric aligned NNW-SSE. Its clast lithologies are predominantly of a Teesdale provenance, with only 4% (greywacke) being of distinctively erratic provenance (D.R. Bridgland pers. comm.). The Dmm is overlain by a coarseningupward sequence comprising planar-bedded sand and interstratified units of matrix-supported and locally clast-supported, cobble to pebble gravel (Gms) and trough cross-bedded gravel and sand. Clast lithologies from the Gms, like the underlying Dmm, are predominantly local in provenance, with only 4% being definitively erratic (D.R. Bridgland, pers. Comm.). The clast forms display slightly higher rounding and less sphericity than those of the underlying Dmm, but are still typical of subglacially derived materials. Finally, the Gms is capped by a further Dmm, with which it has an abrupt but conformable contact. Additionally the base of the Dmm is characterized by a relatively higher concentration of clasts derived from the underlying Gms. Clast sizes then increase vertically in the Dmm.

An unusual glacifluvial landform occurs at a location named the Woolly Hills (Supp. Info. Figure 1 & Figures 18 & 26). This forms a triangular-shaped assemblage of sharp-crested ridges and chaotic high relief hummocks and straddles the watershed separating the Hindon Beck (Gaunless) and Woolly Gill (Spurlswood Beck) drainage basins. Interpreted as a dissected outwash tract by Mills and Hull (1976), the Woolly Hills contain a prominent linear ridge comprising stratified, poorly-sorted gravels and sands, which is aligned partially along the floor of Hindon Beck but also rises over the narrow interfluve to the north before descending into Woolly Gill. More chaotic mounds of glacifluvial material lie to the east on the floor and slopes of Hindon Beck and one such mound forms the elevated site for Woolly Hill farm. As an assemblage the Woolly Hills are remarkable in that they constitute an abnormally large volume of glacifluvial deposits for the upland parts of the study area and also cross underlying drainage basins. They also occur at the western end of a substantial belt of hummocky drift, described above as comprising drift mounds but also containing numerous mounds previously identified as assemblages of glacifluvial deposits (Mills and Hull, 1976). Hence the glacifluvial mounds and ridges of the Woodland/Butterknowle upland together form an elongate assemblage that extends from Hindon Beck to Softley, a distance of 6.5 km (Figure 1b).

4.6.2 Interpretation

The glacifluvial deposits of the study area are all directly ice-contact in origin, with clear evidence of sedimentation over, or at the margins of, receding, topographically-constrained glacier ice. The earliest of these deposits appears to be the Woolly Hills, for which a glacifluvial origin was proposed by Mills and Hull (1976). Their mapping indicated to them that this was a dissected outwash tract. Feeding into the Woolly Hills from the west is the linear gravel and sand ridge in Hindon Beck, for which an esker origin appears to be the most logical given its contents and its linkage to the main glacifluvial complex. Additionally, it climbs out of the valley and over the narrow interfluve into Woolly Gill; only subglacial or englacial meltwater drainage would be able to cross fluvial drainage basins in this way. The more chaotic glacifluvial mounds of the Woolly Hills likely represent the later stages of more advanced glacier melt when meltwater was draining along underlying valleys. Their association with the Butterknowle-Woodland Moraine Belt (BWMB) as a 6.5 km long elongate assemblage in an area previously identified as the likely suture zone of regional (Stainmore) ice and Pennine (Teesdale) ice, as defined by the northernmost extent of regional erratics, indicates that this concentration of glacigenic, especially the glacifluvial, deposits represents the suture zone at the later stages of ice stream activity. At this stage, meltwater would have been draining preferentially along a supraglacial 'valley' and in the associated englacial and subglacial drainage network created at the point of coalescence of two separate ice flow units (cf. Shreve, 1972; Huddart et al., 1999 Gulley et al., 2009a, b).

Within Teesdale, later stages of glacier downwasting are recorded at Cuddy's Bank and Hayberries. At Cuddy's Bank, the architecture of LFAs 2 and 3 reveals scour-and-fill sequences indicative of repeated channel incision and infilling by fluvial processes. This architecture and the abrupt vertical grain size changes, including switches from very poorly sorted gravels to sands, is indicative of iceproximal glacifluvial sedimentation (cf. Miall, 1977, 1978; Maizels, 1993; Marren, 2005). The hummocky bench within which the sedimentary sequence is contained is typical of ice-contact kame terraces and hence the deposits at Cuddy's Banks most likely constitute evidence of former kame terrace construction when glacier ice had become confined to the floor of Teesdale. The altitudinal range of the terrace

and its deposits (<215m OD) is similar to that of the Hayberries-Romaldkirk complex (see below) and therefore is likely related to the same period of glacier karst development during the later stages of deglaciation.
At Hayberries, the lower 5 m thick sequence of rhythmites displays characteristics of deep water sedimentation fed by glacial melt, with phases of traction current activity recorded by sandy bedforms. Areas within the rhythmites where grain size cyclicity is characterized by changes from silts/clays to sands are potentially seasonal and hence could represent varves. The rhythmites are therefore interpreted as glacilacustrine deposits that record the existence of a proglacial lake in the area. Overall the faulting and folding in the rhythmite sequence indicates that it was deposited over buried glacier ice which was undergoing melting beneath the accumulating sediment pile.

The rapid upward-coarsening of the sequence at Hayberries clearly records a change from glacilacustrine to fluvial, likely glacifluvial, sedimentation. However, neither the bedding nor the erosional contacts are everywhere primary but instead constitute fault boundaries. These structures comprise north- to northwest-dipping thrusts and associated asymmetrical east- to southeast verging folds. Generally, the deformation/shearing at the top of stratigraphic sequence must have been induced by glacitectonic deformation, as the bedrock topography to the northwest falls away towards the axis of Teesdale and hence the structures could not be mass movement related.

The architecture of the uppermost facies exposed at Hayberries indicates that the sequence was cross-cut by a large scour infill of interstratified sands and gravels displaying abrupt grain size changes and including two diamicton units. As these deposits relate directly to the surface landform at this site, a complex of discontinuous sinuous ridges, they are interpreted as the basal deposits of an esker infill. The esker developed as part of the extensive valley-side bench of glacifluvial deposits mapped initially by Mills and Hull (1976) and representative of a glacier karst system emerging through kame terrace deposits. The full extent of the underlying glacilacustrine deposits, and hence their role in defining the valley-side bench is unknown. The diamictons in the scour fill sequence truncate and interrupt the glacifluvial sediments and display characteristics of subglacial traction tills (*sensu* Evans et al., 2006; Evans, 2018); clast macrofabrics indicate that the ice responsible for the lower till emplacement was flowing from the north-northwest, which is consistent with the Teesdale-derived clast lithologies in the till and indicative of ice moving towards the southern slopes of Teesdale and therefore of a southeasterly flowing ice lobe centred over the main valley. The occurrence of a coarsening-upward sequence of sands and matrix-supported to clast-supported gravels over the till records a reversion to glacifluvial sedimentation; similar clast lithologies and forms to those of the till suggest that this involved the partial reworking of the till. The uppermost till is also partially derived from the underlying Gms and its vertical increase in clast size and matrixsupport is consistent with this interpretation.

The Hayberries stratigraphy records a sequence of depositional environments as follows. The lower rhythmites and their deformation structures record the development of a supraglacial/proglacial lake in the area. Damming of the Tees to create such a lake could have been achieved by the existence of downstream moraines, for example the Gueswick Moraine. As this moraine reaches an altitude of □220 m OD and the top of the Hayberries exposure is below this at <205 m OD, a moraine-dammed lake origin is a possibility. The coarsening-upwards nature of the lake sediments, culminating in cross-bedded sands and gravels, records lake shallowing and infilling by glacifluvial processes. A significant glacier readvance from the NNW is then recorded by glacitectonic deformation and then subglacial scouring and filling followed as a result of esker sedimentation. This esker sedimentation was then temporarily shutdown by the emplacement of a till by ice flowing from the NNW, as evidenced by the lower Dmm. This likely relates simply to tunnel closure and recoupling of the ice with its bed and hence is not necessarily related to a further significant glacial readvance. The re-establishment of the meltwater tunnel is then recorded by the deposition of the coarsening upwards sequence that caps the till. This upper tunnel fill (esker) was then cannibalized to produce a further till, which records a second tunnel closure/ice-bed coupling event.

The outwash spread mapped by Mills and Hull (1976) from the Gueswick Hills to the southeast of Cotherstone village, was almost certainly fed by meltwater draining laterally from the ice margin when it occupied the Gueswick Moraine. Additionally, breaches along the frontal part of the moraine indicate that overspill water from the lake centred over Hayberries could have also delivered significant volumes of sediment to the outwash spread at a later stage.

4.7 Relict channels and valleys

4.7.1 Description

The north Pennines contain some remarkable relict channels and underfit stream valleys which are developed on valley sides and across lower lying, undulatory to hummocky topography. The valleys have previously been mapped as the former courses of Tertiary and preglacial rivers that drained eastwards on an uplifted, easterly dipping peneplain (Fawcett, 1916; Trotter, 1929a; Mills and Hull, 1976; Figure 4). The linear and parallel (trellised) arrangement of the proposed Tertiary valleys has been explained as a consequent drainage pattern, being controlled by the east-west grain of the Carboniferous bedrock strata. This trellised pattern is thought to have been modified by the development of northwesterly directed headward erosion by subsequent streams, guided in many cases by major fault lines (Fawcett, 1916). Significant in this respect is the development of the modern course of the middle and lower River Tees, which was set up when: 1) a subsequent tributary from the Greta/Hutton Beck/Aldbrough Beck consequents cut a gorge from Barnard Castle to Eggleston and beheaded a number of consequents, capturing the Upper Tees/Langley consequent drainage; and 2) the Eller Beck/Ivor Beck, Hutton Beck and Mannyfold consequents were captured by the Swale drainage, thereby directing the Tees into lower Swaledale. Also significant was the subsequent Eggleston Burn development in a significant N-S orientated valley, which drained into the re-directed Tees drainage. Although Mills and Hull (1976) depict all of these drainage pattern changes taking place in the Tertiary and preglacial times (Figure 4), they provide no specific process for the incision of bedrock and river capture events, hence it is likely, especially as these ancient valleys can be identified in the landscape today, that the events are more recent in age and simply explained as glacial drainage diversions.

Many modern streams occupy portions of the original consequent valleys, albeit at underfit size but some major valleys no longer carry substantial drainage and contain hummocky drift along their floors. Where parts of the former proposed preglacial channels are not visible, it is assumed that they are buried by drift. This drift has been used by Mills and Hull (1976) to conclude that the change to the subsequent drainage pattern took place prior to glaciation, although there is no chronostratigraphic evidence to confirm this. The final major change to the regional fluvial drainage pattern was the capture of the Upper Tees/Greta tributary of the Swale by the “proto-Lower Tees”, forcing the Tees once again to flow eastwards. This event was explained by Mills and Hull (1976) as the product of glaciation; specifically glacier ice blocked the Upper Tees/Greta drainage south of
Barnard Castle, and proglacial lake water spilled northeastward into a small tributary of the protoLower Tees to excavate the Ovington-Winston gorge (Figure 5), the present course of the River Tees.

Significant examples of the proposed consequent valleys can be identified in the landform record. Two of the most prominent of these channels cut directly west-east across the HMB and are named here the Broomielaw/Cleatlam and Forthburn/Sudburn Beck channels (Figure 27). The Broomielaw/Cleatlam channel starts at around 175 m OD in the vicinity of Broomielaw, west of which it is indistinct. The channels contain low amplitude drift mounds around which their present day underfit streams meander. Despite this partial drift infill, the margins of the channels are demarcated by prominent scarps of up to 15 m high and hence it is difficult to envisage them being preglacial valleys unless their courses have been persistently re-occupied by glacial meltwater, potentially subglacial and proglacial, the latter in particular explaining their persistence over long distances through the HMB.

At the western end of Broomielaw channel there are some conspicuous shallow channel fragments and the short gorge of lower Percy Beck. For example, a broad and shallow channel at 165 m OD contains substantial drift mounds around which the underfit Black Beck meanders westwards; the channel indistinctly connects with the Broomielaw/Cleatlam channel near Stainton Grove but streamlined drift appears to have blocked this connection (Figure 27). Further indistinct, short channel segments then occur at around 180 m OD in the vicinity of Quarry Grange and the associated Gravel Hills (2.5 km north of Barnard Castle), the latter interpreted by the BGS as glacifluvial in origin. At lower elevation, an indistinct channel crosses the Barnard Castle golf course at 170 m OD, merging at its eastern end with the 165 m channel of Black Beck. The Percy Beck gorge is deeply incised by 30 m but only in its lower reaches, shallowing out rapidly northwards to form a 300 m wide and distinct channel that connects to the Black Beck channel at 165 m OD. Modern drainage from the north also drains into Percy Beck but is exceptionally underfit within the gorge. To the south of the River Tees in this vicinity are the deeply incised gorges of Deepdale and Scur Beck, whose rivers were capable of a rate of postglacial downcutting that kept pace with that of the River Tees (now at 135 m OD), isolating older Tees cliff terraces at 160 and 150 m OD (Figure 27). The alignment of the Percy Beck and Deepdale gorges, both at right angles to the modern Tees channel, is remarkable and gives the appearance of a former river course that has been cross-cut by the modern Tees alignment.

The largest of the proposed consequent valleys is that of Langleydale, which lies directly below and south of the Woodland/Butterknowle upland and is occupied by the underfit Langley Beck (Figure 16). The valley is approximately 0.4 km wide and □25 m deep but is floored by substantial drift mounds, some of which appear chaotic but also resemble streamlined drift that has been dissected by the cutting of numerous, now relict, channels. These channels descend diagonally from the south facing scarp of the Woodland/Butterknowle upland upon which the largest channel, Arn Gill carries an underfit stream into the River Gaunless drainage basin to the north (Figures 16 & 28a). Arn Gill channel can be traced also westwards to prominent channels cut into the bedrock slopes above Eggleston and Folly Head. The western end of Langleydale connects to substantial bedrock gorges located east of Folly Head, specifically at Pallet Crag Gill and Howe Gill. Two further channels that feed into Pallet Crag Gill originate at around 400 and 350 m OD (Redmire Gill and Goose Tarn Beck respectively; Figures 16 & 28b, c).

The topography below the Grassholme Reservoir dam in Lunedale is unusual for a major valley floor in that it comprises two inset thalwegs, both of which are relatively deep and in places sinuous (Figure 29a). The present course of the River Lune in this area is clearly incised into bedrock in its lower reaches but is choked with heavily dissected, recently extensively quarried, Quaternary deposits at Spring Top, which likely formed a thick infill of deposits. Similarly, the valley containing the underfit stream of Eller

Beck is lined with drift mounds and benches composed of diamicton, around which a larger stream has dissected in inset channel (Figure 29b).

Relict channels exist also on the southern slopes of Monk's Moor and across the Hett Dyke on the southeastern corner of Egglestone Common, where they are responsible for the creation of the bedrock ridges called Knotts (Supp. Info. Figure 1 & Figure 18). The uppermost channel on Monk's Moor descends from around 500 m to 410 m OD, after turning to flow up valley around the Froggerthwaite hummocks and ridges like all the inset meltwater channels on this slope. On the east valley side, the uppermost channel at Knotts is at 450 m OD. A single substantial dry gorge, Sharnberry Gill, cuts across the eastern watershed of the Eggleshope Valley at an altitude of 445 m OD and was interpreted by Dwerryhouse (1902) as a glacial lake spillway. A further isolated, flatfloored dry channel is located at 415 m OD at Blackton Head, which drains into Spurlswood Gill and ultimately the Wear Valley (Figure 18).

A spectacular assemblage of relict channels occurs on the north slopes of lower Lunedale on Moor Rigg where they are incised into bedrock and form an inset sequence trending downslope and downvalley, sub-parallel to the contours (Supp. Info. Figure 1 & Figures 18 & 30). Some channels are densely spaced and hence appear interconnected, giving them the appearance of an anastomosing drainage pattern. A similar sequence but smaller number of channels are incised on the Teesdale side of Moor Rigg and are linked to the substantial Lonton drift mounds (Figure 18). These channels are cross-cut in places by others that trend directly downslope from the crest of Moor Rigg. Less densely spaced and numerous relict channels occur also on the south side of Lunedale, as well as the southern Teesdale slopes of Crossthwaite Common and Holwick Fell. Similar clusters occur on the slopes of Baldersdale and the valley of Maize Beck, south of Cow Green Reservoir (Supp. Info. Figure 1).

4.7.2 Interpretation

The larger scale relict valleys of the study area have been traditionally associated with preQuaternary fluvial drainage networks but their relatively fresh and prominent appearance suggests that most are likely to have been excavated, at least partially, by glacial meltwater. Drainage diversion or thalweg shifts may also be associated with the development of glacial landforms during the latter part of the Quaternary. For example, Mills and Hull (1976) proposed the postglacial blockage of the proto-Tees drainage and its subsequent diversion into its present easterly-orientated channel due to the occurrence of stagnating ice or local 'isostatic upwarp'. This involved a proglacial lake that initially drained through a col at 125 m OD into Hutton Beck and Caldwell Beck (Hutton Magna-Caldwell gorge) but then catastrophically escaped around the receding Teesdale ice lobe to cut the Ovington-Winston gorge to create the present entrenched course of the River Tees at 90 m OD (Figure 31). The former southerly course of the Tees was through a large col at 135 m OD, which now forms the watershed of the southward draining Holme Beck/Gilling Beck (Skeeby Beck drainage). This route was proposed by Mills and Hull (1976) to be the course of the proto-Swale, along which its Upper Tees/Greta tributary previously flowed. This route is lined with glacifluvial deposits (Figure 31) and hence must have served as a meltwater drainage route during deglaciation, potentially at the same time as the Ovington-Winston gorge but then became abandoned as the gorge preferentially incised. As the Skeeby Beck drainage route lies parallel to the lateral moraines on Barningham Moor and Gayles Moor (Figure 12), it was likely exploited by marginal glacial meltwater during downwasting of a lobate ice margin flowing from Teesdale/Stainmore, at the same time as the meltwater channels were being incised into the HMB northeast of Barnard Castle (see below). If Skeeby Beck is also the route of the proto-Tees/Swale it seems unlikely that it would be abandoned by regional drainage in favour of the Ovington-Winston gorge, because it would be driftfilled and hence more easily re-excavated. A potential explanation for its blockage as a protoTees/Swale route could be the initial construction of the Humbleton Mound Belt (HMB), the exact age of which is unknown but would certainly have been initiated prior to the last ice advance out of Teesdale/Stainmore based upon drift plugs in the Broomielaw/Cleatlam and Forthburn/Sudburn Beck channels. A deglacial blockage is also possible as evidenced by a cluster of arcuate moraines located at 140-145 m OD at Newsham, on the Skeeby Beck watershed (Figure 12), giving further reinforcement to the Ovington-Winston gorge meltwater piracy theory of Mills and Hull (1976). Until further details are available on the ages of the infills of all the meltwater and proposed precursor river channels in the area, the evolution and pattern of long term drainage development will remain largely speculative.

The course of the proto-Tees and its relationship to the HMB can be further assessed in the area to the north of the Ovington-Winston gorge, between Barnard Castle and Cleatlam. Here the Broomielaw/Cleatlam and Forthburn/Sudburn Beck channels do contain drift fills indicative of their formation (and therefore the formation of the HMB which they dissect) at least prior to the last glaciation but their prominent scarp margins are indicative of more recent occupation by glacial meltwater (Figure 27). A morainic genesis for the HMB, as proposed above, implicates a postTertiary origin for the channels, because they cross-cut the HMB ridges. This meltwater could have been subglacial and/or proglacial. A proglacial origin appears to be most likely given the persistence of the channels through the HMB and the west to east descents of their long profiles. Also noticeable is the drop in west end elevations from 200 m OD in the north to 170 m OD in the south, indicative of recession and thinning of the Teesdale ice lobe and gradual exposure of lower terrain over which its marginal to proglacial meltwater could drain. The postglacial Tees was established once the relatively lower terrain to the southwest, over Barnard Castle was uncovered, documented by the cutting of terraces at 160 and 150 m between the mouths of Scur Beck and Deepdale; the more direct easterly route through the Ovington-Winston gorge was initiated by the southernmost of the meltwater channels cutting through the HMB.

The origins of the shallow channel fragments and the short gorge of lower Percy Beck are more enigmatic. It is unliklely that the Percy Beck gorge was cut over such a short distance by postglacial drainage from the small drainage basin to the north. So some form of this channel must have existed prior to postglacial incision and its northern extension could be manifest in the broad and shallow 165 m channel that runs south of Stainton Grove (Black Beck) and then connects indistinctly with the Broomielaw/Cleatlam channel. A significant infill of sand and gravel occurs in this area as discovered during construction work at The Hub on the northeast edge of Barnard Castle. The 170 m channel that crosses the Barnard Castle golf course also converges on this location. Like the Broomielaw/Cleatlam and Forthburn/Sudburn Beck channels, the channels that converge on and include Percy Beck are likely pre-LGM drainage courses, the depth of which could be close to that of the modern Tees (i.e. close to the base of Percy Beck). The remarkable alignment of Percy Beck and
Deepdale is also likely not a coincidence and hence it is proposed that they represent the alignment of the precursor Deepdale tributary to the Tees when it occupied a course that ran through the present location of the golf course. From here the Tees could have flowed into the Black Beck channel and then into the Broomielaw/Cleatlam channel, which is as low as 120 m OD in its central stretch, joining with the channel occupied by the modern Tees at Selaby Hall, where the exit of Ovington-Winston gorge now delivers the Tees after its more southerly diversion around the higher terrain of the HMB. So the Broomielaw/Cleatlam channel is hypothesized here to be the proto-Tees valley, partially blocked with drift during the last glaciation and then partially re-excavated by glacial meltwater during

deglaciation; it was blocked to eastward flowing regional drainage due to a thick drift plug north of Barnard Castle and/or piracy of the drainage by a relatively more deeply incised meltwater channel immediately west of Barnard Castle.

The drift infills of the two inset thalwegs of lower Lunedale indicate that they existed prior to the last glaciation and that glacial meltwater partially re-excavated them, likely subglacially and then proglacially. The underfit Eller Beck has a steeper long profile below the Grassholme dam (Figure 29a) and presently drains out of its large host channel and into the low amplitude drift mounds of West End, Mickleton, where it eventually disappears into the groundwater. Because its valley is wider and lies more central to the main axis of Lunedale, it is tempting to promote the Eller Beck thalweg as the likely route of the proto-Lune. This implies that the present course of the River Lune may have been preferentially cleared of its drift plug and excavated to a deeper level than the Eller Beck thalweg by the concentration of glacial meltwater on the steeper north side of Lunedale, evidenced by the dense network of lateral meltwater channels below Moor Rigg; although most meltwater was being drained laterally to the former glacier snout, most of the lateral meltwater channel bases feed into the River Lune channel (Figure 30).

The numerous relict channels that cross the hummocky drift fill of Langleydale and descend diagonally from the south facing scarp of the Woodland/Butterknowle upland are all interpreted as glacial meltwater channels due to their lack of integration into normal fluvial drainage networks. They record meltwater incision at the margin of glacier ice downwasting from the scarp top. Early lateral meltwater incision at the margins of this ice was concentred on Arn Gill, which drains into the River Gaunless drainage basin to the north of the fault scarp summit and can be traced back to prominent channels cut into the bedrock slopes above Eggleston and Folly Head. Once the ice margin had downwasted below the scarp summits of Peatmoor Crag and Cragg Top/Penny Hill, lateral meltwater began draining southeastwards and into the Langleydale drainage basin. At later stages of ice recession, meltwater continued to be diverted into the floor of Langleydale via substantial bedrock gorges to the east of Folly Head, specifically at Pallet Crag Gill and Howe Gill, thereby initiating the later stages of incision of the drift infill. The heads of these later stage incisions lie at the eastern margins of the Folly Head/Windy Hill ridges of the Gueswick Hills Moraine and hence record proglacial meltwater drainage from the ice margin that occupied this moraine (Figures 16 & 18); on the hillslope above the moraine, the Redmire Gill and Goose Tarn Beck channels also carried meltwater from altitudes of 400 and 350 m OD to Pallet Crag Gill. The moraine descends in altitude from 330 m OD at Folly Head to 320 m OD at Windy Hill, before dropping to a 275 m OD lateral moraine south of High Shipley. The heads of the proglacial meltwater channels on the distal side of the moraine similarly drop in altitude from around 325 m OD at Folly Head to 290-295 m OD north of High Shipley, where an extensive glacifluvial outwash spread forms a bench on the side of Teesdale. This outwash spread was deposited after the earlier drainage from the Teesdale ice margin into Howe Gill was terminated, eliminating the drainage of water from the Teesdale ice margin into Langleydale.

The large volume of meltwater that was diverted into the Arn Gill/Gaunless drainage basin and then Langleydale is unusual in that glacier ice lay over significantly lower topography to the south, especially over Teesdale, and therefore meltwater had to be flowing at high levels within the ice in order for it to be delivered into the easterly draining valleys. Ice-marginal or lateral meltwater drainage would have been capable of such a flow pattern and indeed lateral meltwater channels exist on the southern slopes of Monk's Moor and also across the Hett Dyke on the southeastern corner of Egglestone Common, where they are responsible for the creation of the bedrock ridges called Knotts (Supp. Info. Figure 1 & Figure 18). The uppermost channel on Monk's Moor descends from around 500 m to 410 m OD, after turning to flow up valley around the Froggerthwaite Moraine like all the inset meltwater channels on this slope. On the east valley side, the uppermost channel at Knotts is at 450 m OD. In order to cut channels at isolated locations at such high altitudes on both sides of the Egglestone Burn valley, water flow would have to be ice-directed and hence is further evidence, in addition to the Froggerthwaite Moraine, that a lobe of Teesdale ice backfilled the lower half of the valley. Indeed this pattern of drainage channel development was regarded by Mills and Hull (1976) as evidence for glacial lake spillways, whereby the upper Egglestone Burn valley was dammed by Teesdale ice to form a lake (hereby called Glacial Lake Eggleshope). This lake was also proposed by Dwerryhouse (1902), who identified the substantial dry gorge of Sharnberry Gill, which cuts across the eastern watershed of the valley at an altitude of 445 m OD, as the northern lake spillway (Figure 18). This spillway carried the lake waters into Euden Beck and ultimately to the River Wear drainage basin but was terminated as an outlet once the lower channels at Knotts were incised. The flat-floored dry channel located at 415 m OD at Blackton Head indicates that spillway waters entered the Wear drainage basin via that route after Sharnberry Gill ceased to operate. This would have required ice to be occupying the Blackton Head area but it is likely that marginal meltwater was draining along the south slopes of Grey Carrs to enter the Redmire Gill channel at 400 m OD at around the same time, when the Gueswick Hills Moraine was being constructed. The final drainage of Glacial Lake Eggleshope was likely subglacial, beneath the thinning Teesdale ice lobe, as evidenced by a small esker remnant (Mills and Hull, 1976) inside the Froggerthwaite Moraine. The lack of glacilacustrine deposits suggests that it was a short-lived lake, but the size of the Froggerthwaite Moraine is consistent with a substantial stillstand and/or readvance of the Teesdale ice and so an alternative explanation for sparse lake sediments is that the lake drained frequently, potentially creating jokulhlaups that could at least partially explain the significant erosion of the gorges below Redmire Gill and Goose Tarn Beck and even have contributed to the deep incision of Arn Gill and the Gaunless valley.

The overall pattern of the Moor Rigg relict channels on the north slopes of lower Lunedale is typical of channels cut by ice-marginal meltwater. This meltwater drained along the margins of downwasting valley glacier ice, in this case receding westwards up Lunedale (Figure 30). The similar sequence of channels incised on the Teesdale side of Moor Rigg and linked to the Lonton laterofrontal moraine (see above) are also interpreted as lateral meltwater channels. The channels that descend from the crest of Moor Rigg to cross-cut these lateral channels were clearly incised by meltwater generated by the Lunedale ice margin during its early stages of downwasting from the crest summit. Additionally, other channels, also fed by Lunedale meltwater, cross Moor Rigg and join the Teesdale lateral channels. The receding right margin of the Lunedale valley glacier is demarcated by the less densely spaced lateral meltwater channels on the south valley side. The receding right margin of the Teesdale valley ice is similarly demarcated by lateral meltwater channels on Crossthwaite Common and Holwick Fell. The clusters of valley-side channels in Baldersdale and the valley of Maize Beck also record valley-confined ice recession.

5. Palaeoglaciological reconstruction and wider implications

The subglacially streamlined landforms (drumlins) of Teesdale and Stainmore Gap record the passage of ice streams dispersing from the centre of the BIIS when it was at its most extensive, as well as during its early stages of thinning and recession. This strong easterly flow over the Pennine Escarpment was driven by ice dispersal from an arcuate ice divide located over the central Eden Valley and extending through the Lake District and Howgill Fells in the period 25-22 ka BP (Livingstone et al. 2012). This is recorded by Livingstone et als. (2008) flowsets ST1 and ST2 (Figure 3). This style of regional ice flow was responsible for watershed breaching (Figure 20) and interaction with locally based plateau icefields (Figure 2), the latter being forced to switch from early stages of presumed radial flow (Trotter, 1929a) to strong easterly flow as an ice flow unit composed of Teesdale and Weardale ice streams constricted by the more vigorous Stainmore Gap ice stream to the south and Tyne Gap ice stream to the north (Livingstone et al., 2008, 2010b, 2012, 2015).

Flow set ST3 records more topographically confined ice flow within Teesdale, driven by the location of an ice divide over the Pennine Escarpment and arching round the heads of Teesdale and Weardale in the period 22-20 ka BP; by this time the regionally driven Stainmore Gap ice stream had shutdown. Livingstone et al. (2012, 2015) propose that this flow direction persisted until around 20 ka BP, at which time the Teesdale ice margin occupied the Feldom Moraine and ice flow in middle Teesdale was directed more southeasterly. This is around the time of the Blackhall Wood-Gosforth Oscillation (Livingstone et al., 2015). A North Pennine icefield, nourishing topographically confined ice flow within Teesdale, is depicted by Livingstone et al. (2015) as persisting until at least 16 ka BP, the time of the Scottish Readvance; they tentatively place the ice margin at this time around the location of Barnard Castle but propose no specific landform to demarcate this limit more precisely.

Due to the lack of thick till cover and dominance of bedrock subglacial bedforms over much of the palaeo-ice stream footprints of the region, it is possible that only a partial record of flowset overprinting has been preserved. More complex ice flow directional changes appear to be recorded in the few multiple till exposures such as at Stack Holme and Cow Green. At Stack Holme complex ice dynamics are indicated by the repeated temporal switching of ice flow from W-E to SW-NE during the accretion of subglacial deforming layer tills. This shows that the two flowsets ST 1 and ST 2, recorded in the subglacial bedforms, did not simply replace one another but instead were repeatedly superimposed, thereby explaining why flowsets are difficult to differentiate in the Stainmore Gap. A strong southwesterly flow by Stainmore ice, likely when it was at its strongest, is recorded by LFA 1 at Cuddy’s Bank, a subglacial till emplaced by ice flowing into Teesdale and transporting regional erratics that could only be brought to the area by Stainmore ice. This is consistent with the site being located immediately south of the Teesdale/Stainmore ice suture zone, as demarcated by the distribution of regional erratics (Figure 3). At Cow Green the till fabrics and drumlin alignments appear to record both topographically constrained ice flow (to the south or southeast), during a phase of more restricted glacier coverage, as well as regionally directed flow (to the east or eastsoutheast; i.e. flowset ST 4); even the WSW-ENE aligned clast macrofabric at Dubbysike can be reconciled with flowset ST 4.

The streamlined mounds (drumlins) of the Cow Green area (Mitchell, 2007) are significant with respect to two, not mutually exclusive, critical concepts in glacial geomorphology. First, they form the up-ice end of a continuum of drumlinization, which ranges from discrete mounds in upper Teesdale to elongate drumlins near Barnard Castle, reflected in elongation ratios of 1.73-2.2 to 13.75. This downflow trend has been explained as the product of increasing ice flow velocity by Dyke and Morris (1988), Clark and Stokes (2001) and Stokes and Clark (2002), especially on palaeo-ice stream beds, and has been applied to North Pennines drumlins by Mitchell (1994). However, local perturbations have been reported, specifically where ovoid shaped landforms lying amongst more elongate features appear to relate to lithological changes in the glacier bed (e.g. Piotrowski & Vahldiek 1991; Rose, 1987). The Holwick drumlins constitute an obvious example of such a local perturbation and likely represent “drumlin clones” as defined by Clark (2010). If their valley floor position and elongation anomaly does indeed represent a pre-drumlinization accumulation of sediments, then they conceivably mark a former valley glacier marginal moraine that was glacially overrun and streamlined. A more convincing example of this is manifest in the Harwood Beck crossvalley ridge at Low End (Figure 15). Second, the volume of glacigenic debris that comprises the upper Tees drumlin field is anomalous for a location that is only 5-10 km from summits displaying evidence of extensive blockfields and hence negligible erosion; how does glacier ice generate matrixsupported diamictons (tills) up to 10 m thick over such a large area after travelling such a short distance? The answer to this question likely lies in not just the volume but also the pattern of glacigenic drift around Cow Green and Harwood Beck. The arcuate assemblages of partially streamlined drift mounds here resemble latero-frontal moraines that have been glacially overrun. The positioning of these moraines could conceivably be related to the establishment of glacier margins during phases of “average glacial conditions” as defined by Porter (1989). He proposed that most of the Quaternary Period has been characterized by an Earth surface with an intermediate style of glacier coverage, which for the British Isles was similar to that of the Younger Dryas Stade. These conditions are the most effective in terms of longer term landscape change because they dominate for most of the time and hence constitute average conditions over longer time periods. In terms of the positioning of substantial glacigenic drift accumulations in terrains like the North Pennines, both regional (Hubbard et al., 2009) and local (Evans et al., 2012; Evans and Jamieson, 2017) numerical glacier modelling demonstrates that the highest plateaux are likely to have been occupied by ice for the longest cumulative period of time throughout the Quaternary; hence such “average” glacial conditions are likely to have been responsible for marked increases in glacigenic drift thicknesses on formerly glacierized uplands (cf. “zone of thick drift” of Kleman et al. 2008; Evans 2016) and the resulting morainic landforms, such as those in upper Teesdale, are streamlined but not removed by shorter lived phases of regional ice streaming.

A similar overridden moraine genesis is proposed for the HMB, although this is based almost entirely upon its arcuate plan form due to a lack of significant exposure through the constituent mounds. Some confidence in the notion that large scale glacitectonic disturbance could create a moraine belt of this size is provided by the origins of the Tow Law, Bullman Hills and Lambgreen Hills bedrock rafts, which indicate that the nature of the horizontally bedded strata of the North Pennines, particularly their arrangement in cyclothems, appears to have made them susceptible to glacitectonic displacement or megablock/raft production.

The juxtaposition of locally (Pennine) and regionally (Scottish) sourced ice streams and the evidence for their suture zone, in the form of erratic distribution (Dwerryhouse, 1902), makes Teesdale a prime location for understanding and gathering diagnostic criteria for inter-ice stream geomorphology. Although the northernmost limit of regional erratics (Supp. Info. Figure 1) marks the maximum incursion of regional ice, the suture zone between Stainmore and Pennine ice over Teesdale will have migrated over time, specifically moving southward during deglaciation in response to Pennine ice, flowing along Teesdale (flowsets ST 3 and 4), replacing the Stainmore Gap ice stream. Little is known about the nature of landform-sediment assemblages at sites of ice stream interaction in upland settings. Ice stream shear margin moraines have been reported from lowland settings (Stokes and Clark, 2002; Hindmarsh and Stokes, 2008) and from continental shelves (Batchelor and Dowdeswell, 2016; Dowdeswell et al., 2016) and the development of significant assemblages of glacifluvial deposits or interlobate moraines have been recognized in ancient ice sheet records, where meltwater processes and sediments become preferentially concentrated at the suture zones of different ice flow units (Dyke and Dredge, 1989; Brennand and Shaw, 1996; Punkari, 1997; Barnett et al., 1998; Pugin et al., 1999; Makinen, 2003; Russell et al., 2003). Modern analogues for the preferential development of eskers in medial moraine zones and supraglacial troughs have also been reported from the receding margins of Svalbard and Icelandic glaciers (Price, 1973; Huddart et al., 1999; Russell et al., 2001; Evans and Twigg, 2002; Storrar et al., 2015). This concentration of meltwater processes is explained by Shreve’s (1972) hydraulic theory, wherein conduits will converge on elongate interlobate depressions, and Gulley et als. (2009a, b) observations on cut-and-closure type incisions of meltwater streams in interlobate depressions. Based upon their location adjacent to the Pennine/Stainmore ice suture zone or the northern limit of regional erratics as well as their west-east alignment, the Cockfield Moraine and ButterknowleWoodland Moraine Belt (BWMB) most likely represent inter-ice stream deposits produced during the early stages of ice stream decoupling (Figure 32). A similar positioning and orientation of the glacifluvial assemblage on the Woodland/Butterknowle upland, including the Woolly Hills and various other deposits mapped further east by Mills and Hull (1976), suggests that they too likely originated as inter-ice stream eskers. Indeed, the unusual fan-shaped assemblage of the Woolly Hills resembles that of the re-entrant infill created during the 1996 jökulhlaup at Skeiðararjökull (Russell et al., 2001). A similar jökulhlaup origin for the Woolly Hills would be consistent with the catastrophic drainage of the earliest ice-dammed lakes formed in the northern tributaries of Teesdale during deglaciation (see below).

Although Livingstone et al. (2015) have tentatively proposed a Teesdale-based ice lobe position for the Scottish Readvance, very little is known about the later stages of the last glaciation in the North Pennines and no significant moraines likely to record ice recession have ever been identified inside the Feldom Moraine. The development of first the Hutton Magna-Caldwell gorge and then the Ovington-Winston gorge routes for the modern River Tees appears to have been the result of the infilling of the original Skeeby Beck route by morainic drift, as proposed by Mills and Hull (1976). This drift is at least partly related to the large assemblage of latero-frontal moraines lying inside the Feldom Moraine, but blocking of this drainage route may have taken place initially during earlier glaciations. Indeed, the Broomielaw/Cleatlam channel appears to be the proto-Tees valley when it flowed directly from west to east (Figure 27). We can further speculate that the river Tees has occupied each of the west-east aligned channels (Broomielaw-Cleatlam; Ovington-Winston; Hutton Magna-Caldwell) more than once over the Quaternary Period, depending on the preferential incision of drift infills of the various thalwegs by glacial meltwater.

To the west of the Feldom Moraine, our mapping has identified significant drift mound belts and associated meltwater channels, especially to the west of Barnard Castle. These record oscillations of a glacier lobe in mid-Teesdale during the advanced stages of ice recession in Lunedale but well after the apparent shutdown of the Stainmore Gap ice stream (Figures 18 & 33). Sequential stages of recession are named after the prominent landforms used in their demarcation and the former glacier ice surfaces can be reconstructed using the extent and altitudes of these landform assemblages (Figure 34), assuming normal values of basal shear stress and hence a parabolic ice surface profile. The Glacial Lake Eggleshope stage is the uppermost and therefore earliest of the topographically-confined ice stages, associated with the development of the Sharnberry Gill/Euden Beck spillway and hence a glacial lake dammed in the Eggleshope Beck valleys as well as the highest of the meltwater channels on Monk's Moor, Knotts Hole and Redmire Gill. Ice was likely occupying upper Langleydale at this time, because meltwater (in addition to overspill water from Glacial Lake Eggleshope) was being diverted into the huge channels of Arn Gill and the Gaunless Valley. The subsequent Mill Hill stage is reconstructed using primarily the Froggerthwaite moraine in the Eggleston Burn valley and the Mill Hill moraine, but also the upper lateral moraines on Bail Hill on the south side of Teesdale as well as the uppermost morainic mounds in the Folly Head/Windy Hill area. Proglacial meltwater was discharged from the latter margin into the upper reaches of Langleydale at this time (Figure 18). The following, Gueswick stage is demarcated by the Gueswick end moraine and its associated lateral moraines on lower Bail Hill. Inset within this is the Hayberries stage, demarcated by latero-frontal moraine ridges on the lower slopes of West Barnley and the slopes immediately above Hayberries and Mickleton. This glacier snout was most likely associated with the development of the Hayberries-Romaldkirk esker complex and its overriding by ice to produce a till in the upper glacifluvial deposits at Hayberries; this is inferred not only because of altitudinal compatibility but also because the north to south orientated stress direction recorded in the till is compatible with the compressive radial ice flow directions in a lobate snout. Between the Gueswick and Hayberries stages it appears from the lower facies at Hayberries that a morainedammed lake existed up-valley and therefore dammed by the Gueswick Moraine; this lake must have existed prior to a potential readvance to the Hayberries area during the Hayberries stage, because the lake deposits are first cross-cut by esker deposits and then capped by tills. Finally, a more restricted cover of decoupling glacier lobes can be reconstructed using the Lonton Moraine and the uppermost lateral moraines of Teesdale and Lunedale ice on Moor Rigg, hereby termed the Lonton stage but relating to ice lobes in Teesdale and the Lune Valley.

The palaeoglaciological reconstruction depicted in Figure 33 indicates that the Blackhall WoodGosforth Oscillation ice divide, depicted by Livingstone et al. (2015) as being located over the Stainmore Gap, was still operating at the Lonton Stage, because ice in Lunedale was feeding meltwater to lateral channels near Lonton/Laithkirk. This indicates that a Pennine-based icefield was more extensive than that depicted by Livingstone et al. (2015) and still occupied the lower topography of the Stainmore Gap at around the time of the Scottish Readvance. If any or a combination of the Mill Hill, Gueswick, Hayberries and Lonton stages represent a phase of plateau icefield stillstand or readvance in the North Pennines then a more extensive moraine belt should be manifest in the upper tributaries of the Tees drainage. This is likely represented by the north-south aligned assemblage of the Burners Hills, Knotts Hills, Tute Hill moraine and Seven Hills in the middle and south part of the Stainmore Gap. The proposed frozen snout plucking origins of these locally derived bedrock block moraines is compatible with a lateral meltwater origin of the densely-spaced network of channels at the Lonton stage limit in Lunedale (Figure 30). Such lateral channel networks have been widely related to the existence of former cold-based glacier margins (Dyke, 1993) and in Britain have been identified in similar positions of advanced ice sheet recession, where they constitute evidence for the glacier lobation created by topographic control on glacier flow (Greenwood et al., 2007; Livingstone et al., 2010a; Evans et al., 2017). Hence both the lateral meltwater channels and the Lonton stage moraines, stretching from the Lune Valley to the Seven Hills on south Stainmore, potentially record the temporary development of cold-based or polythermal ice conditions around the margins of a plateau-based icefield, a situation that would not be unusual considering the numerous oscillations in climate that characterized the later stages of the last glacial cycle. The apparently relatively steep glacier surface profile during the Lonton stage (Figure 34) conceivably relates to the cold based or polythermal conditions (i.e. higher basal shear stress) that prevailed at that time.

The later stages of ice recession from upper Teesdale are recorded by the Widdy Bank latero-frontal moraines. These record the former existence of a small valley glacier below Cauldron Snout and likely fed by plateau-based ice flowing through Cow Green. Because previous reconstructions of Younger Dryas (Loch Lomond Stadial) ice in the region indicate only localized cirque or niche glaciers (Manley, 1961; Wilson and Clark, 1995; Mitchell, 1996), the Widdy Bank moraines must date to a phase of ice stillstand or readvance that predates the Younger Dryas and post-dates the Lonton stage.

Conclusions

Geomorphological mapping and sedimentological analysis of the glacial landforms of Teesdale and the adjacent North Pennines and Stainmore Gap identified six landform categories including: i) bedrock controlled features; ii) discrete mounds and hills; iii) drift mounds; iv) streamlined landforms; v) glacifluvial outwash and depositional ridges; and vi) relict channels and valleys. This evidence has been employed to: a) decipher the evolution of the BIIS over the northern Pennines, at the location of the suture zone between locally-sourced Pennine plateau ice and the regional Stainmore Gap ice stream; and b) reconstruct for the first time the style of deglaciation in the North Pennines as it pertains to ice sheet marginal responses to regional climate change at the close of the last glaciation. A number of significant conclusions on these aspects of investigation can be proposed:

- Although subglacial bedform flowsets can be used to identify the major ice flow directions/flow phases in the palaeo-ice stream signature, more complex flow dynamics are recorded in multiple tills in valley-floor drumlin exposures. This indicates that the subglacial bedform record is a blend, a likely typical scenario in areas of discontinuous till cover and extensive bedrock erosional landforms.
- A down-valley trend in drumlin elongation ratios (1.73-2.2 to 13.75) is the product of increasing ice flow velocity, but local perturbations likely represent “drumlin clones” at the locations of former valley glacier marginal moraines that have been glacially overrun.
- The arcuate assemblages of partially streamlined drift mounds that comprise the upper Tees drumlin field are likely to be glacially overridden latero-frontal moraines potentially demarcating former glacier margins during phases of “average glacial conditions” and thereby constitute an example of a glacial palimpsest landscape.
- Significant concentrations of glacigenic debris aligned ice flow-parallel and draped over the bedrock-controlled topographic grain, can be explained as inter-ice stream assemblages, including ice-stream interaction or shear moraines and interlobate glacifluvial depo-centres.
- Although re-incised by meltwater during deglaciation, the Broomielaw/Cleatlam channel appears to be the proto-Tees valley. The Hutton Magna-Caldwell and Ovington-Winston gorges were also occupied by deglacial meltwater but the latter became the course of the modern River Tees due to the infilling of the original Skeeby Beck route by morainic drift. It is likely that the River Tees has occupied each of these west-east aligned channels more than once over the Quaternary Period.
- Oscillations of a glacier lobe in mid-Teesdale during deglaciation are marked by five inset assemblages of moraines and associated drift and meltwater channels, all of which postdate the shutdown of the Stainmore Gap ice stream. These are named the Glacial Lake Eggleshope, Mill Hill, Gueswick, Hayberries and Lonton stages.
- The lateral meltwater channels and the Lonton stage moraines, including the bedrock-cored moraines in the central Stainmore Gap, appear to record the temporary development of cold-based or polythermal ice conditions around the margins of a plateau-based icefield dating approximately to the Scottish Readvance.

Acknowledgements

Thanks to Stephen Livingstone with help in manipulating the DEM of northern England. Thanks to reviewers Jim Rose and Andrew Finalyson for constructive comments.

References

Aber, J.S., Croot, D.G., Fenton, M.M., 1989. Glaciotectonic Landforms and Structures. Kluwer, Dordrecht.

Andrews, J.T., 1972. Glacier power, mass balances, velocities and erosion potential. Zeitschrift fur Geomorphologie 13, 1-17.

Arthurton, R.S., Wadge, A. J., 1981. Geology of the country around Penrith. Memoir of the Geological Survey of Great Britain.

Aveline, W.T., Hughes, T. McK., 1888. The Geology of the Country around Kendal, Sedbergh, Bowness and Tebay. Memoir of the Geological Survey of England and Wales.

Ballantyne, C.K., 2013. Trimlines and palaeonunataks. In: Elias, S. (Ed.), Encyclopedia of Quaternary Science, Second Edition. Elsevier, Amsterdam, pp. 918-928.

Ballantyne, C.K., McCarroll, D., Nesje, A., Dahl, S.O., 1997. Periglacial trimlines, former nunataks and the dimensions of the last ice sheet in Wester Ross, northwest Scotland. Journal of Quaternary Science 12, 225-238.

Barnett, P.J., Sharpe, D.R., Russell, H.A.J., 1998. On the origin of the Oak Ridges Moraine. Canadian Journal of Earth Sciences 35, 1152-1167.

Batchelor, C.L., Dowdeswell, J.A., 2016. Lateral shear-moraines and lateral marginal-moraines of palaeo-ice streams. Quaternary Science Reviews 151, 1-26.

Benn, D.I., 1994. Fabric shape and the interpretation of sedimentary fabric data. Journal of Sedimentary Research A 64, 910–915.

Benn, D.I., 1995. Fabric signature of subglacial till deformation, Breiðamerkurjokull, Iceland. Sedimentology 42, 735–747.

Benn, D.I., 2004a. Macrofabric. In: Evans, D.J.A., Benn, D.I., (eds): A Practical Guide to the Study of Glacial Sediments. Arnold, London, pp. 93–114.

Benn, D.I., 2004b. Clast morphology. In: Evans, D.J.A., Benn, D.I., (eds.), A Practical Guide to the Study of Glacial Sediments. Arnold, London, pp. 77-92.

Benn, D.I., Ballantyne, C.K., 1994. Reconstructing the transport history of glaciogenic sediments: a new approach based on the co-variance of clast form indices. Sedimentary Geology 91, 215227.

Benn, D.I., Evans, D.J.A., 1996. The interpretation and classification of subglacially-deformed materials. Quaternary Science Reviews 15, 23–52.

Bennett, M.R., Huddart, D., Glasser, N.F., 1999. Large scale bedrock displacement by cirque glaciers. Arctic, Antarctic and Alpine Research 31, 91-107.

Bluemle, J.P., Clayton, L., 1984. Large scale glacial thrusting and related processes in North Dakota. Boreas 13, 279-299.

Bonham-Carter, G.F., 1994. GIS for Geoscientists. Elsevier Science, Oxford.

Boulton, G.S., 1987. A theory of drumlin formation by subglacial deformation. In: Rose, J., Menzies, J. (Eds.), Drumlin Symposium. Balkema, Rotterdam, pp. 25–80.

Boulton, G.S., 1996a. Theory of glacial erosion, transport and deposition as a consequence of subglacial sediment deformation. Journal of Glaciology 42, 43–62.

Boulton, G.S., 1996b. The origin of till sequences by subglacial sediment deformation beneath mid-latitude ice sheets. Annals of Glaciology 22, 75–84.

Bowen, D.Q. (ed.), 1999. A Revised Correlation of Quaternary Deposits in the British Isles. Geological Society Special Report 23

Boyce, J.I., Eyles, N., 1991. Drumlins carved by deforming till streams below the Laurentide Ice Sheet. Geology 19, 787-790.

Boyce, J.I., Eyles, N., 2000. Architectural element analysis applied to glacial deposits: internal geometry of a late Pleistocene till sheet, Ontario, Canada. Bulletin of the Geological Society of America 112, 98–118.

Brennand, T.A., Shaw, J., 1996. The Harricana glaciofluvial complex, Abitibi region, Quebec: its genesis and implications for meltwater regime and ice sheet dynamics. Sedimentary Geology 102, 221-262.

Bridgland, D.R., Innes, J.B., Long, A.J., Mitchell, W.A., 2011. Late Quaternary Landscape Evolution of the Swale–Ure Washlands, North Yorkshire. Oxbow Books, Oxford, 325 pp.

Burgess, I.C., Holliday, D.W., 1979. Geology of the country around Brough-under-Stainmore. Memoir of the Geological Survey of Great Britain, England and Wales, Sheet 31.

Clark, C.D., 1993. Mega-scale lineations and cross-cutting ice flow landforms. Earth Surface Processes and Landforms 18, 1-29.

Clark, C.D., 2010. Emergent drumlins and their clones: from till dilatancy to flow instabilities. Journal of Glaciology 56, 1011-1025.

Clark, C.D., Stokes, C.R., 2001. Extent and basal characteristics of the M'Clintock Channel ice stream. Quaternary International 86, 81-101.

Clark, C. D., Ely, J. C., Greenwood, S. L., Hughes, A. L. C., Meehan, R., Barr, I. D., Bateman, M. D., Bradwell, T., Doole, J., Evans, D. J. A., Jordan, C. J., Monteys, X., Pellicer, X. M., Sheehy, M., 2018. BRITICE Glacial Map, version 2: a map and GIS database of glacial landforms of the last British–Irish Ice Sheet. Boreas 47, 11–27.

Dakyns, J.R., Tiddeman, R.H., Gunn, W. & Strahan, A. 1890a. The Geology of the Country around Ingleborough, with Parts of Wensleydale and Wharfedale. Memoir of the Geological Survey of England and Wales.

Dakyns, J.R., Tiddeman, R.H., Russell, R., Clough, C.T. & Strahan, A. 1890b. The Geology of the Country around Mallerstang, with Parts of Wensleydale, Swaledale and Arkengarthdale. Memoir of the Geological Survey of England and Wales.

Dakyns, J.R., Tiddeman, R.H., Russell, R., Clough, C.T. & Strahan, A. 1891. The geology of the country around Mallerstang with parts of Wensleydale, Swaledale and Arkendale. Sheet 97NW Memoir of the Geological Survey of Great Britain HMSO, London.

Dowdeswell, J.A.**,** Ottesen, D., Rise, L., 2016. Landforms characteristic of inter-ice stream settings on the Norwegian and Svalbard continental margins. Geological Society Memoir 46, 437-444.

Dunlop, P., Clark, C.D., Hindmarsh, R.C.A., 2008. The Bed Ribbing Instability Explanation (BRIE): testing a numerical model of ribbed moraine formation arising from coupled flow of ice and subglacial sediment. Journal of Geophysical Research 10.1029/2007JF000954.

Dwerryhouse, A.R., 1902. The glaciation of Teesdale, Weardale, and the Tyne valley, and their tributary valleys. Quarterly Journal of the Geological Society of London 58, 572-608.

Dyke, A. S., 1993. Landscapes of cold-centred Late Wisconsin ice caps, Arctic Canada. Progress in Physical Geography 17, 223-247.

Dyke, A.S., Dredge, L.A., 1989. Quaternary geology of the northwestern Canadian Shield. In: Fulton, R.J. (ed.), Quaternary Geology of Canada and Greenland. Geological Survey of Canada, Geology of Canada, 1, 178-214.

Dyke, A.S., Morris, T.F., 1988. Drumlin fields, dispersal trains and ice streams in Arctic Canada. Canadian Geographer 32, 86-90.

Ely, J.C., Clark, C.D., Spagnolo, M., Stokes, C.R., Greenwood, S.L., Hughes, A.L., Dunlop, P., Hess, D., 2016. Do subglacial bedforms comprise a size and shape continuum? Geomorphology 257, 108-119.

Evans, D.J.A., 2016. Landscapes at the periphery of glacierization – retrospect and prospect. Scottish Geographical Journal 132, 140-163.

Evans, D.J.A., 2017. Bullman Hills and Lambgreen Hills – glacitectonic bedrock rafts or landslide blocks? In: Evans, D.J.A. (Ed.), The Quaternary Landscape History of Teesdale and the North Pennines – Field Guide. QRA, London, pp. 228-230.

Evans, D.J.A., 2018. Till – A Glacial Process Sedimentology. Wiley-Blackwell, Chichester.

Evans, D.J.A., Benn, D.I., 2004. Facies description and the logging of sedimentary exposures. In: Evans, D.J.A., Benn, D.I. (Eds.), A Practical Guide to the Study of Glacial Sediments. Arnold, London.

Evans, D.J.A., Hiemstra, J.F., 2005. Till deposition by glacier sub-marginal, incremental thickening. Earth Surface Processes and Landforms 30, 1633–1662.

Evans, D.J.A., Jamieson, S.S.R., 2017. The North Pennines climate and glacierization: plateau icefields and the concept of average glacial conditions. In: Evans, D.J.A. (Ed.), The Quaternary Landscape History of Teesdale and the North Pennines – Field Guide. Quaternary Research Association, London, pp. 68-75.

Evans, D.J.A., Phillips, E.R., in prep. Glacitectonic disturbance of a glacilacustrine and glacifluvial sedimentary sequence in Teesdale, northern England: implications for North Pennine glacier reconstructions. Proceedings of the Yorkshire Geological Society.

Evans, D. J. A., Twigg, D. R., 2002. The active temperate glacial landsystem: A model based on Breiðamerkurjökull and Fjallsjökull, Iceland. Quaternary Science Reviews 21, 2143–2177.

Evans, D. J. A., Harrison, S., Vieli, A., Anderson, E., 2012. The glaciation of Dartmoor: the southernmost independent Pleistocene ice cap in the British Isles, Quaternary Science Reviews 45, 31–53.

Evans D.J.A., Phillips E.R., Hiemstra J.F., Auton C.A., 2006. Subglacial till: formation, sedimentary characteristics and classification. Earth Science Reviews 78, 115-176.

Evans, D.J.A., Livingstone, S.J., Vieli, A., Ó Cofaigh, C., 2009. The palaeoglaciology of the central sector of the British and Irish Ice Sheet: reconciling glacial geomorphology and preliminary ice sheet modelling. Quaternary Science Reviews 28, 739–757.

Evans, D.J.A., Owen, L.A., Roberts, D.H., 1995. Stratigraphy and sedimentology of Devensian (Dimlington Stadial) glacial deposits, east Yorkshire, England. Journal of Quaternary Science 10, 241–265.

Evans, D.J.A., Hiemstra, J.F., Ó Cofaigh, C., 2007. An assessment of clast macrofabrics in glacigenic sediments based on A/B plane data. Geografiska Annaler 89A, 103-120.

Evans, D.J.A., Hughes, A.L.C., Hansom, J.D., Roberts, D.H., 2017. Scottish Landform Examples 43: Glacifluvial landforms of Strathallan, Perthshire. Scottish Geographical Journal 133, 42-53.

Evans D.J.A., Roberts D.H., Evans S.C., 2016. Multiple subglacial till deposition: a modern exemplar for Quaternary palaeoglaciology. Quaternary Science Reviews 145, 1-21.

Eyles, N., Sladen, J.A., Gilroy, S., 1982. A depositional model for stratigraphic complexes and facies superimposition in lodgement tills. Boreas 11, 317–333.

Krabbendam, M., Eyles, N., Putkinen, N. Bradwell, T., Arbelaez-Moreno, L., 2016. Streamlined 'hard beds' cut by paleo-ice streams: a preliminary review. Sedimentary Geology 338, 24-50.

Eyles, N., Putkinen, N, Sookhan, S., Arbelaez-Moreno, L., 2016. Erosional origin of drumlins and megaridges. Sedimentary Geology 338, 2-23.

Eyles, N., Doughty, M., 2016. Glacially-streamlined hard and soft beds of the paleo-Ontario Ice Stream in central Canada. Sedimentary Geology 338, 51-71.

Fawcett, C.B., 1916. The Middle Tees and its tributaries: a study in river development. Geographical Journal 48, 310-325.

Fenton, M.M., 1987. Deformation terrain on the northern Great Plains. In: Graf, W.L. (Ed.), Geomorphic Systems of North America. Geological Society of America Special Volume 2, pp. 176-182.

Fowler, A. C., 2000. An instability mechanism for drumlin formation. In: Maltman, A.J., Hubbard, B., Hambrey, M.J. (Eds.), Deformation of Glacial Materials. Geological Society, London, Special Publications, vol. 176, pp. 307–319.

Fowler, A.C., 2009. Instability modelling of drumlin formation incorporating leeside cavity growth. Proceedings of the Royal Society of London, Series A 465, 2681-2702.

Fowler, A.C., 2010. The instability theory of drumlin formation applied to Newtonian viscous ice of finite depth. Proceedings of the Royal Society of London, Series A 466, 2673-2694.

Francis, E.A., 1970. Quaternary. In: Hickling, G. (ed.). Geology of Durham County. Transactions of the Natural History Society, Northumberland 41, 134-152.

Greenwood, S.L., Clark, C.D., Hughes, A.L.C., 2007. Formalising an inversion methodology for reconstructing ice-sheet retreat patterns from meltwater channels: application to the British Ice Sheet. Journal of Quaternary Science 22, 637–645.

Gregory, K.J., 1965. Proglacial Lake Eskdale after sixty years. Transactions of the Institute of British Geographers 36, 149-162.

Gulley, J., Benn, D.I., Luckman, A., Muller, D., 2009a. A cut-and-closure origin for englacial conduits on uncrevassed parts of polythermal glaciers. Journal of Glaciology 55, 66-80.

Gulley, J., Benn, D.I., Screaton, L., Martin, J., 2009b. Mechanisms of englacial conduit formation and implications for subglacial recharge. Quaternary Science Reviews 28, 1984-1999.

Hicock, S.R., Goff, J.R., Lian, O.B., Little, E.C., 1996. On the interpretation of subglacial till fabric. Journal of Sedimentary Research 66, 928-934.

Hiemstra, J.F., Evans, D.J.A., Ó Cofaigh, C., 2007. The role of glacitectonic rafting and comminution in the production of subglacial tills: examples from southwest Ireland and Antarctica. Boreas 36, 386-399.

Hindmarsh, R.C.A., Stokes, C.R., 2008. Formation mechanisms for ice stream lateral shear margin moraines. Earth Surface Processes and Landforms 33, 610-626.

Hollingworth, S. E., 1931. Glaciation of western Edenside and adjoining areas and the drumlins of the Edenside and Solway Basin. Quarterly Journal of the Geological Society, London 87**,** 281-359.

Hubbard, A., Bradwell, T., Golledge, N., Hall, A., Patton, H., Sugden, D., Cooper, R., Stoker, M., 2009. Dynamic cycles, ice-streams and their impact on the extent, chronology and deglaciation of the British–Irish Ice Sheet. Quaternary Science Reviews 28, 758–776.

Huddart, D., Bennett, M.R., Glasser, N.F., 1999. Morphology and sedimentology of a high arctic esker system: Vegbreen, Svalbard. Boreas 28, 253-273.

Ives, J. D., 1978. The maximum extent of the Laurentide Ice Sheet along the east coast of North America during the last glaciation. Arctic 31, 24–53.

Jansson, K.N., Kleman, J., 1999. The horned crag-and-tails of the Ungava Bay landforms swarm, Quebec-Labrador, Canada. Annals of Glaciology 28, 168-174.

Jarman, D., 2006. Large rock slope failures in the Highlands of Scotland: characterisation, causes and spatial distribution. Engineering Geology 83, 161-182.

Johnson, G.A.L., Dunham, K.C., 1963. The geology of Moorhouse. Monograph of the Nature Conservancy.

Kendall, P.F., Wroot, H.E., 1924. Geology of Yorkshire. EP Publishing, Wakefield.

Kennard, M.F., Reader, R.A., 1975. Cow Green dam and reservoir. Proceedings of the Institution of Civil Engineers 58, 147-175.

Kleman, J. & Glasser, N. F. 2007. The subglacial thermal organisation (STO) of ice sheets. *Quaternary Science Reviews* 26, 585-597.

Kleman, J., Stroeven, A. P., Lundqvist, J., 2008. Patterns of Quaternary ice sheet erosion and deposition in Fennoscandia and a theoretical framework for explanation. Geomorphology 97, 73–90.

Krabbendam M., Bradwell T., 2011. Lateral plucking as a mechanism for elongate erosional glacial bedforms: explaining megagrooves in Britain and Canada. Earth Surface Processes and Landforms 36: 1335–1349.

Krabbendam, M., Eyles, N., Putkinen, N., Bradwell, T., Arbeleaz-Moreno, L., 2016. Streamlined hard beds formed by palaeo-ice streams: a review. Sedimentary Geology 338, 24–50.

Lewkowicz, A.G., 1990. Morphology, frequency and magnitude of active-layer detachment slides, Fosheim Peninsula, Ellesmere Island, NWT. Proceedings, Fifth Canadian Permafrost Conference, Quebec City. Nordicana 54, 111-118.

Lewkowicz, A.G., 1992. Factors influencing the distribution and initiation of active-later detachment slides on Ellesmere Island, Arctic Canada. In, Dixon, J.C. & Abrahams, A.D. (eds.), Periglacial Geomorphology. Wiley, Chichester, pp. 223-250.

Leysinger-Vieli, G.J.M.C., Gudmundsson, G.H., 2010. A numerical study of glacier advance over deforming till. The Cryosphere 4, 359-372.

Livingstone, S.J., Ó Cofaigh, C., Evans, D.J.A., 2008. Glacial geomorphology of the central sector of the last British–Irish Ice Sheet. Journal of Maps 2008, 358–377.

Livingstone, S.J., Evans, D.J.A., Ó Cofaigh, C., Hopkins, J., 2010a. The Brampton Kame Belt and Pennine Escarpment Meltwater Channel System (Cumbria, UK). Morphology, Sedimentology and Formation: Proceedings of the Geologists' Association 121, 423–443.

Livingstone, S.J., Ó Cofaigh, C., Evans, D.J.A., 2010b. A major ice drainage pathway of the last British–Irish Ice Sheet: the Tyne Gap, northern England. Journal of Quaternary Science 25, 354–370.

Livingstone, S.J., Evans, D.J.A., Ó Cofaigh, C., Davies, B.J., Merritt, J.W., Huddart, D., Mitchell, W.A., Roberts, D.H., Yorke, L., 2012. Glaciodynamics of the central sector of the last British–Irish Ice Sheet in Northern England. Earth-Science Reviews 111, 25-55.

Livingstone, S.J., Roberts, D.H., Davies, B.J., Evans, D.J.A., Ó Cofaigh, C., Gheorghiu, D.M., 2015. Late Devensian deglaciation of the Tyne Gap Palaeo-Ice Stream, northern England. Journal of Quaternary Science 30, 790-804.

Lukas, S., Benn, D.I., Boston, C.M., Brook, M., Coray, S., Evans, D.J.A., Graf, A., Kellerer-Pirklbauer, A., Kirkbride, M.P., Krabbendam, M., Lovell, H., Machiedo, M., Mills, S.C., Nye, K., Reinardy, B.T.I., Ross, F.H., Signer, M., 2013. Clast shape analysis and clast transport paths in glacial environments: a critical review of methods and the role of lithology. Earth-Science Reviews 121, 96-116.

Lunn, A.G., 1995a. Quaternary. In: Johnson, G.A.L. (Ed.) Robson's Geology of North East England. Transactions of the Natural History Society of Northumberland 56, 296-311.

Lunn, A.G., 1995b. The Quaternary of South Tynedale. In: Scrutton, C. (Ed.), Northumbrian rocks and landscape: a field guide. Yorkshire Geological Society & Ellenbank Press, Maryport, pp. 137-145.

Lunn, A. G., 2004. Northumberland. New Naturalist Series. Harper-Collins, London.

Maag, H., 1969. Ice-Dammed Lakes and Marginal Glacial Drainage on Axel Heiberg Island, Axel Heiberg Island Research Report. Montreal: McGill University.

Maizels, J.K., 1993. Lithofacies variations within sandur deposits: the role of runoff regime, flow dynamics and sediment supply characteristics. Sedimentary Geology 85, 299–325.

Mäkinen, J., 2003. Time-transgressive deposits of repeated depositional sequences within interlobate glaciofluvial (esker) sediments in Köyliö, SW Finland. Sedimentology 50, 327-360.

Manley, G., 1961. Solar variations, climatic change and related geophysical problems. *Nature* 190, 967-968.

Marren, P.M., 2005. Magnitude and frequency in proglacial rivers: a geomorphological and sedimentological perspective. Earth Science Reviews 70, 203-251.

McCabe, A.M., Clark, P.U., 1998. Ice-sheet variability around the North Atlantic Ocean during the last deglaciation. Nature, 392, 373-377.

McCabe, A.M., Clark, P.U., Clark, J., 2005. AMS 14 C dating of deglacial events in the Irish Sea Basin and other sectors of the British–Irish ice sheet. Quaternary Science Reviews 24, 1673-1690.

McCabe, A.M., Clark, P.U., Clark, J., Dunlop, P., 2007. Radiocarbon constraints on readvances of the British–Irish Ice Sheet in the northern Irish Sea Basin during the last deglaciation. Quaternary Science Reviews 26, 1204-1211.

McCarroll, D., 2016. Trimline trauma: the wider implications of a paradigm shift in recognizing and interpreting glacial limits. Scottish Geographical Journal 132, 130-139.

McMillan, A.A., Hamblin, R.J.O. & Merritt, J.W. 2011. *A Lithostratigraphical Framework for Onshore Quaternary and Neogene (Tertiary) Superficial Deposits of Great Britain and the Isle of Man*. British Geological Survey Research Report, RR/10/03.

Miall, A.D., 1977. A review of the braided river depositional environment. Earth Science Reviews 13, 1-62.

Miall, A.D., 1978. Lithofacies types and vertical profile models in braided river deposits: a summary. In: Miall, A.D. (Ed.), Fluvial Sedimentology. Canadian Society of Petroleum Geologists, Memoir 5, 597-604.

Mills, A.B., 1976. View from the crop: a glimpse of the unusual glacial rafting of coal in Durham. The Opencast Geologist 1, 16-17.

Mills, D.A.C., Hull, J.H., 1976. Geology of the country around Barnard Castle. Memoir of the Geological Survey of Great Britain.

Mitchell, W.A., 1991a. *Glaciation of upper Wensleydale and adjoining watershed regions.* PhD thesis, University of London.

Mitchell, W. A., (ed.) 1991b. *Western Pennines: Field Guide.* Quaternary Research Association, London.

Mitchell, W.A., 1994. Drumlins in ice sheet reconstructions with reference to the western Pennines, northern England. Sedimentary Geology 93, 313-331.

Mitchell, W.A., 1996. Significance of snowblow in the generation of Loch Lomond Stadial (Younger Dryas) glaciers in the western Pennines, northern England. *Journal of Quaternary Science* 11, 233-248.

Mitchell, W.A., 2007. Reconstructions of the Late Devensian (Dimlington Stadial) British-Irish Ice Sheet: the role of the upper Tees drumlin field, northern Pennines, England. Proceedings of the Yorkshire Geological Society 56, 221–234.

Mitchell, W. A., Huddart, D., 2002. Cross Fell (NY 687 344). In: Huddart, D., Glasser, N. F. (Eds.) Quaternary of Northern England. Geological Conservation Review Series, No. 25. Joint Nature Conservation Committee, Peterborough, 334-343.

Mitchell, W. A., Letzer, J. M., 2006. Drumlin map of the western Pennines and southern Vale of Eden. *Journal of Maps* 2006, 10-16 .

Mitchell, W.A., Bridgland, D.R., Innes, J.B., 2010. Late Quaternary evolution of the Tees-Swale interfluve east of the Pennines: the role of glaciation in the development of river systems in northern England. Proceedings of the Geologists'Association 121, 410–422.

Moore, E.N., 1994. Glacial Geology and Geomorphology of Weardale. Unpublished PhD thesis, University of Durham.

Onorati, G., Poscolieri, M., Ventura, R., Chiarini, V., Crucilla, U., 1992. The digital elevation model of Italy for geomorphology and structural geology. Catena 19 147–178.

Phillips, E.R., Auton, C.A., 2008. Microtextural analysis of glacially ‘deformed’ bedrock: implications for inheritance of preferred clast orientations in diamictons. Journal of Quaternary Science 23, 229-240.

Phillips, W.M., Hall, A.M., Mottram, R., Fifield, L.K. & Sugden, D.E. 2006. Cosmogenic ^{10}Be and ^{26}Al exposure ages of tors and erratics, Cairngorm Mountains, Scotland: timescales for the development of a classic landscape of selective linear glacial erosion. *Geomorphology* 73, 222-245.

Piotrowski, J., Vahldiek, J., 1991. Elongated hills near Schonhorst, Schleswig-Holstein: drumlins or terminal push moraines? Bulletin of the Geological Society of Denmark 38, 231-242.

Porter, S.C., 1989. Some geological implications of average Quaternary glacial conditions. Quaternary Research 32, 245-261.

Pounder, E., 1989. Classic landforms of the Northern Dales. Classic Landforms Guide No. 10. Geographical Association, Sheffield.

Price, R.J., 1973. Glacial and Fluvioglacial Landforms. Longmans, London.
Pugin, A., Pullan, S.E., Sharpe, D.R., 1999. Seismic facies and regional architecture of the Oak Ridges Moraine area, southern Ontario. Canadian Journal of Earth Sciences 36, 409-432.
Punkari, M., 1997. Glacial and glaciofluvial deposits in the interlobate areas of the Scandinavian ice sheet. Quaternary Science Reviews 16, 741-753.
Raistrick, A., 1926. The glaciation of Wensleydale, Swaledale and the adjoining parts of the Pennines. Proceedings of the Yorkshire Geological Society 20, 366-410.
Raistrick, A., 1931. The late-glacial and post-glacial Periods in the North Pennines. Transactions of the Northern Naturalists Union Part I, 16-29.
Raistrick, A., 1932. The correlation of retreat stages across the Pennines. Proceedings of the Yorkshire Geological Society 22, 199-214.
Rea, B. R., Evans, D. J. A., 2003. Plateau icefield landsystems. In: Evans, D. J. A. (Ed.), Glacial Landsystems, 407-431. Arnold, London.
Rea, B. R., Whalley, W. B., Evans, D. J. A., Gordon, J. E., McDougall, D. A., 1998. Plateau Icefields: Geomorphology and Dynamics. Quaternary Proceedings 6, 35-54.
Rose, J., 1980. Landform development around Kisdon, upper Swaledale, Yorkshire. Proceedings of the Yorkshire Geological Society 43, 201-219.
Rose, J., 1987. Drumlins as part of a glacier bedform continuum. In: Menzies, J., Rose, J. (eds.), Drumlin Symposium. Balkema, Rotterdam, 103-116.
Rose, J., Letzer, J.M., 1977. Superimposed Drumlins. Journal of Glaciology 18, 471-480.
Russell, A.J., Knudsen, O., Fay, H., Marren, P.M., Heinz, J., Tronicke, J., 2001. Morphology and sedimentology of a giant supraglacial, ice-walled, jokulhlaup channel, Skeidarárjökull, Iceland: implications for esker genesis. Global and Planetary Change 28, 193–216.
Russell, H.A.J., Arnott, R.W.C., Sharpe, D.R., 2003. Evidence for rapid sedimentation in a tunnel channel, Oak Ridges Moraine, southern Ontario, Canada. Sedimentary Geology 160, 33-55.
Searle, R.C., Young, B., Mwandoe, E., 2016. The Palaeogene Armathwaite-Cleveland Dyke in Upper Teesdale, northern England: magnetic characteristics and relationship to mineralization. Proceedings of the Yorkshire Geological Society 61, 148-154.
Shreve, R.L., 1972. Movement of water in glaciers. Journal of Glaciology 11, 205-214.
Smith, M.J., Clark, C.D., 2005. Methods for the visualization of digital elevation models for landform mapping. Earth Surface Processes and Landforms 30, 885-900.
Smith, M.J., Rose, J., Booth, S.J., 2006. Geomorphological mapping of glacial landforms from remotely sensed data: an evaluation of the principal data sources and an assessment of their quality. Geomorphology 76, 148-165.
Spagnolo, M., Clark, C.D., Hughes, A.L.C., 2012. Drumlin relief. Geomorphology 153-154, 179-191.
Stalker, A. MacS., 1976. Megablocks, or the enormous erratics of the Albertan prairies. Geological Survey of Canada Paper 76-1C, 185–188.
Stokes, C.R., Clark, C.D., 2002. Ice stream shear margin moraines. Earth Surface Processes and Landforms 27, 547-558.
Stokes, C.R., Fowler, A.C., Clark, C.D., Hindmarsh, R.C.A., Spagnolo, M., 2013. The instability theory of drumlin formation and its explanation of their varied composition and internal structure. Quaternary Science Reviews 62, 77-96.
Stokes, C.R., Spagnolo, M., Clark, C.D., 2011. The composition and internal structure of drumlins: complexity, commonality, and implications for a unifying theory of their formation. Earth Science Reviews 107, 398–422.
Stone, P., Millward, D., Young, B., Merritt, J.W., Clarke, S.M., McCormac, M., Lawrence, D.J.D., 2010. British Regional Geology: Northern England (Fifth edition). (Keyworth, Nottingham: British Geological Survey).

Storrar, R. D., Evans, D. J. A., Stokes, C. R., Ewertowski, M., 2015. Controls on the location, morphology and evolution of complex esker systems at decadal timescales, Breiðamerkurjökull, SE Iceland. Earth Surface Processes and Landforms 40, 1421-1438.

Sugden, D.E., Glasser, N.F., Clapperton, C.M., 1992. Evolution of large roches moutonnées. Geografiska Annaler 74A, 253-264.

Syverson, K.M., Mickelson, D.M., 2009. Origin and significance of lateral meltwater channels formed along a temperate glacier margin, Glacier Bay, Alaska. Boreas 38, 132–145.

Taylor, B.J., Burgess, I.C., Land, D.H., Mills, D.A.C., Smith, D.B., Warren, M.A., 1971. Northern England. Fourth edition. British Regional Geology. Natural Environment Research Council, Institute of Geological Sciences, HMSO: London.

Trotter, F.M., 1929a. On the glaciation of eastern Edenside, Alston Block and the Carlisle Plain. Quarterly Journal of the Geological Society of London 85, 549-612.

Trotter, F.M., 1929b. The Tertiary uplift and resultant drainage of the Alston Block and adjacent areas. Proceedings of the Yorkshire Geological Society 21, 161-180.

Trotter, F.M., Hollingworth, S.E., 1932a. The Geology of the Brampton District. Memoir of the Geological Society, HMSO, London.

Trotter, F.M., Hollingworth, S.E., 1932b. The glacial sequence in the North of England. Geological Magazine 69, 374–380.

Tsui, P.C., Cruden, D.M., Thomson, S., 1989. Ice thrust terrains and glaciotectonic settings in central Alberta. Canadian Journal of Earth Sciences 26, 1308-1318.

Tufnell, L., 1969. The range of periglacial phenomena in northern England. *Biuletyn Peryglacjalny*, 19, 291-232.

Tufnell, L. 1985. Periglacial landforms in the Cross Fell – Knock Fell area of the northern Pennines. In: Boardman, J. (ed.), Field Guide to the Periglacial Landforms of Northern England, Quaternary Research Association, pp. 414.

Vincent, P.J., 1969. The glacial history and deposits of a selected part of the Alston Block. PhD thesis, University of Durham.

Wells, A.J., 1955. The glaciation in the Teesdale-Swaledale watershed. Proceedings of the University of Durham Philosophical Society 12, 82-93.

Whalley, W.B., 2009. On the interpretation of discrete debris accumulations associated with glaciers with special reference to the British Isles. In: Knight, J., Harrison, S., (Eds.), Periglacial and Paraglacial Processes and Environments. Geological Society of London Special Publication 320, London, 85-102.

Whalley, W.B., 2012. Using Discrete Debris Accumulations to Help Interpret Upland Glaciation of the Younger Dryas in the British Isles. In: Piacentini, T., Miccadei, E. (Eds.), Studies on Environmental and Applied Geomorphology. InTech Europe, Rijeka.

Whalley, W.B., 2015. Discrete Debris Accumulations in the Lake District and their role in the interpretation of past processes and climate. In: McDougall, D.A., Evans, D.J.A. (Eds.), The Quaternary of the Lake District – Field Guide. Quaternary Research Association, London, pp. 97-107.

Wilson, P., Clark, R., 1995. Landforms associated with a Loch Lomond Stadial glacier at Cronkley Scar, Teesdale, northern Pennines. Proceedings of the Yorkshire Geological Society 50, 277283.

Figure captions

Figure 1: Maps of the study region and field area: a) physiography (NEXTMap) and location map of Teesdale and the northern England region. White box indicates the study area; b) large scale physiography (NEXTMap) and location map with major features and place names for Teesdale and

adjacent areas. Abbreviations are as follows: BCC – Broomielaw-Cleatlam channel; BH – Blackton Head; BH/LG – Bullman Hills/Lambgreen Hils; CB – Cuddy's Bank; GC – Grey Carrs; HB – Hindon Beck; LC – Langleydale Common; RG – Redmire Gill; WF – Widdybank Fell; WH – Woolly Hills.

Figure 2: Map of Upper Teesdale and adjacent areas showing the former ice flow directions depicted by Dwerryhouse (1902) at a relatively early stage of ice flow up the Vale of Eden from Scotland. Note the radial flow of the Pennine-centred ice from the Cross Fell plateau and the deflection of easterly flowing Tyne Gap and Stainmore Gap ice streams around this ice. Also shown are the proposed nunataks of the north Pennines from Dwerryhouse (1902) and Raistrick (1931), features now interpreted as the levels of thermal regime changes in the overlying ice sheet. Red lines demarcate the limit of regional, western-derived erratics and thereby outline areas characterised by Pennine erratics only (after Trotter, 1929; Vincent, 1969; Taylor *et al.,* 1971).

Figure 3: Annotated NEXTMap DEM of Teesdale, the Stainmore Gap, Yorkshire Dales and northern Vale of York showing flow sets and important moraines (from Livingstone et al., 2012). Also marked as black lines for later reference are major moraines in Teesdale and on the Stanmore Gap, the latter being outlined in black and including the Burners Hills (BH), the Knotts Hills (KH), the Seven Hills (SH) and the Tute Hill moraine (THM). The Ovington-Winston Gorge is labelled OW Gorge.

Figure 4: Maps of proposed pre-Quaternary drainage routes based on major valleys and valley fragments (from Mills and Hull, 1976).

Figure 5: NEXTMap image of the study area, showing the distribution of landform types and annotated with the main physiographic zones and locations.

Figure 6: Examples of glacitectonic bedrock mega-rafts from the study region: a) the Sunniside and Broom Hill interfluve glacitectonic rafts, near Tow Law, County Durham (after Mills (1974) and Moore (1994); b) views within and across the Bullman Hills from the east (upper) and southwest (lower), showing the flat-topped nature of the mounds and the surface outcrops of the Great Limestone that comprises the core of the landform assemblage. Location geology map is a simplified extract from EDINA Digimap (©NERC 2015) showing the bedrock geology of the Cross Fell area. Red cross hatch denotes areas of proposed landslips, here interpreted as megablock erratics for the Bullman and Lambgreen hills.

Figure 7: NEXTMap DEM extract showing the main landforms in the Cotherstone Moor area and the adjacent terrain to the south around Sleightholme Beck. The features are interpreted as rubble moraine/bedrock megarafts and moraines comprising local bedrock fragments and blocks.

Figure 8: Ground views of the Seven Hills, located southwest of Bowes, at the southern margin of the Stainmore Gap. Exposures of fragmented limestone are apparent wherever vegetation has been removed by controlled burning. Views are towards the south (upper panel), southeast (lower left panel) and west (lower right panel).

Figure 9: The Burners Hills. Upper panel shows their locally conical forms (view towards the northwest). Lower panel is a north-facing exposure through mudstone bedrock below the hills, showing an upper 1-2 m thick crushed zone of densely spaced anastomosing partings/fissility, capped by <2 m of mudstone-rich, matrix-supported diamicton.

Figure 10: NEXTMap DEM showing the landforms of upper Teesdale. The NE illumination angle highlights the sinuous pattern in the alignment of some discrete mounds and hills, especially in the Harwood Beck/west Herdship Fell area (yellow dotted lines). Also clearly visible are streamlined

landforms displaying a down-valley trend in increasing elongation, from Mitchell's (2007) drumlins around Cow Green Reservoir to more spindle-like shapes in Teesdale.

Figure 11: The discrete mounds and hills (drumlins, Mitchell, 2007) of the Cow Green area. Photographs are views of the drift mounds/drumlins to the west of Cow Green Reservoir, showing both elongate (top view looking southwest) and ovoid (lower view looking east) forms. Local stream incision and resulting slumping of the mound margins is also visible. Right panel shows clast macrofabric data from diamicton exposures around Cow Green Reservoir. Stereonets show clast Aaxis macrofabrics from the lower, middle and upper diamictons in the stratigraphy exposed at the east shoreline and from a lower Dmm near Dubbysike, at the west end of the reservoir. MLA = mean lineation azimuth. The clast macrofabric shape ternary diagram shows the Cow Green data in relation to envelopes of Icelandic upper tills (green) and lower tills (red) and lodged clasts (blue). Also shown is the shape development pathway in relation to consolidation and shear strain as proposed by Iverson et al. (2008). CGL, CGM and CGU = Cow Green lower, middle and upper respectively. DSL = Dubbysike lower.

Figure 12: NEXTMap DEM showing the landforms of lower Teesdale and upper Skeeby Beck and extending slightly further south and east of the main study area depicted in Supplementary Information Figure 1. Strongly streamlined terrain in Teesdale (red lineations represent streamlined landform crests) terminates at the arc of discrete mounds and hills (brown outlines) of the Humbleton Mound Belt (HMB), the boundaries of which are demarcated by the red outline. The previously recognized Barningham Moor moraines are marked by black ridge symbols at bottom centre. Other prominent drift mounds and ridges mapped as black lines are the Gueswick Hills assemblage at top left and the western extensions of Bridgland et als. (2011) Great Smeaton Moraine, south of Darlington. Relict (meltwater) channels are marked by blue arrows.

Figure 13: West-facing exposure through disturbed sandstone strata at High Shipley quarry, showing fracturing and deformation of the upper strata above the dashed line.

Figure 14: NEXTMap DEM extract of the central part of the Humbleton mound belt immediately east of Barnard Castle, showing major mounds outlined in orange and sinuous (potential esker) ridge outlined in yellow. Note also the rectilinear scarps. Also well illustrated is the abrupt boundary separating the drumlinized terrain of Teesdale and the mounds (thick red dashed line). The Broomielaw channel is visible at the top of the image. HH = Humbleton Hill.

Figure 15: The large cross-valley drift ridge near Low End in Harwood Beck viewed from the west. Valley side ridges descend diagonally down the slope to the left to join the valley floor ridge (arrowed).

Figure 16: Annotated NEXTMap DEM extract, showing the main landforms and the extent of hummocky drift in the Langleydale/Folly Head area and its relationship to the linear bedrock grain, apparent as stepped slope profiles and ridge summits. Also shown is the underfit stream valley of Arn Gill and the gorges of Redmire Gill, Goose Tarn Beck, Pallet Crag Gill and Howe Gill. The likely position of the Langleydale buried valley is also depicted. The Woolly Hills glacifluvial assemblage is mapped in yellow. Blue arrows demarcate the major relict (meltwater) drainage pathways.

Figure 17: Ground views, looking north, of the Tute Hill drift ridge, showing its low amplitude and internal composition of bouldery diamicton (see also Figure 7).

Figure 18: Major glacial landforms mapped on the NEXTMap DEM in the area of mid-Teesdale and Lunedale (see also Supplementary Information Figure 1), showing selected altitudinal values in meters OD. Green areas are glacigenic drift mounds and ridges, orange areas are glacifluvial mounds interpreted either as eskers or kames, and yellow arrows represent selected relict (meltwater)

channels associated with the drift mounds and ridges. Locations are: EV = Eggleshope Valley; SG = Sharnberry Gill; F = Froggerthwaite; K = Knotts (Hett Dyke); BH = Blackton Head; M-in-T = Middletonin-Teesdale; MR = Moor Rigg; L = Lonton; RM = Romaldkirk Moor; R = Romaldkirk; GH = Gueswick Hills; FH = Folly Head/Windy Hill; MH = Mill Hill; C = Cotherstone; HB = Hindon Beck; WH = Woolly Hills.

Figure 19: The Gueswick Hills drift mounds assemblage and its north valley side counterparts: a) the Gueswick Hills (arrowed behind the buildings) viewed from the south; b) part of the Folly Head/Windy Hill mounds (viewed from the south); c) linear drift ridge descending the north slopes of Teesdale from High Shipley (viewed from the southeast); d) the continuation of the High Shipley linear drift ridge (right foreground) towards the floor of Teesdale (viewed from the west).

Figure 20: NEXTMap image showing watershed breaching by subglacial streamlining in the high col between Mickle Fell and Little Fell. The underlying bedrock structure is still visible through lineations and discrete mounds or potential bedrock rafts.

Figure 21: View down valley from Holwick of the impressive streamlined mounds or drumlins (arrowed) on the south side of the Teesdale valley floor. Seats Hill is the nearest mound.

Figure 22: Stratigraphy and sedimentology of the Stack Holme drumlin section, showing the main lithofacies and sedimentary structures: a) clast macrofabrics; b) clast form data; c) analytical diagrams for clast macrofabric (upper) and clast form using co-variance of RA and C40 (lower). The clast macrofabric shape ternary diagrams show the data from the Stack Holme diamicton samples (left plot) in relation to envelopes of Icelandic upper tills (dotted line) and lower tills (solid line) and lodged clasts (grey; right plot). Also shown in the right plot is the shape development pathway in relation to consolidation and shear strain as proposed by Iverson et al. (2008).

Figure 23: The Mickleton-Egglestone glacifluvial terrace: main view is along the terrace from the east from the area directly west of the Hayberries esker complex; inset is an exposure through the edge of the terrace at The Mill (NY 967245), showing poorly-sorted boulder to cobble gravels with imbrication recording meltwater flows from the west

Figure 24: The Cuddy’s Bank section: Upper panels are a photomontage and sketch log of the LFAs. Lower panel shows a clast lithological count from LFA 1, indicating predominantly local materials and minor regional erratic components. Right hand column shows the results of a clast macrofabric sample (Schmidt lower hemisphere stereoplot) and clast form sample from LFA 1, indicating a NESW clast alignment and a blocky and subrounded form signature typical of subglacial materials.

Figure 25: Sediments and stratigraphy at Hayberries: a) typical vertical profile log and photographs of main facies; b) annotated photograph panorama showing the architecture of the major sedimentary units and the erosional scour infill.

Figure 26: Glacial landforms on Langleydale Common and the west end of the BWMB highlighted on a NEXTMap DEM extract. Brown areas are interpreted as morainic drift and green areas as the Woolly Hills esker complex. Question mark denotes an unknown origin due to the lack of sediment exposures. Cowley Ridge and its 14 m thick till content is from Mills and Hull (1976). Inset photograph is a view of the Woolly Hills from the south.

Figure 27: Extract from the NEXTMap DEM showing the details of the palaeochannels associated with the HMB to the east of Barnard Castle. Major channels are marked by large yellow dashes and

minor channels by small yellow dashes. Black numbers refer to altitudes in meters OD of channel intakes and termini, and along the River Tees are the altitudes of the modern floodplain.

Figure 28: Relict channels in the Langleydale and Woodland/Butterknowle upland area: a) the Arn Gill channel near Kinninvie looking downflow towards the east; b) aerial photograph mosaic (OS Crown Copyright) of the bedrock incised channels and gorges around the head of Langleydale. Dashed arrows mark minor lateral channels. Dotted lines mark initiation points or heads of Howe Gill and unnamed gorge; c) the gorges of the upper Pallet Crag channel network around Holdsworth Farm. Upper view is wide angle shot of the main channel. Inset photograph shows the details of a landslide developed in drift (diamicton) which filled the channel prior to its re-excavation.

Figure 29: Evidence of the proto-Lune in lower Lunedale and around the village of Mickleton: a) cross profiles of the River Lune and Eller Beck thalwegs in lower Lunedale, below the Grassholme reservoir dam; b) the Eller Beck valley looking upstream and viewed from the northwest (top) and northeast (bottom). The steep sides of the most recent incised channel and the drift benches plugging the larger valley are evident in both views.

Figure 30: The glacial landforms of lower Lunedale on an annotated NEXTMap DEM extract. This shows the *en echelon* arrangement of lateral meltwater channels and their relationship with the Lonton Moraine and meltwater channels associated with former Teesdale ice. Also visible are streamlined mounds (drumlins) around which channels have been incised. The pattern of Lunedale ice recession, as defined by the lateral channels, is marked by broken black lines.

Figure 31: Simpified geology map modified from EDINA Digimap extract (©NERC 2015), showing the surficial geology and main drainage routes related to glacier ice recession into Teesdale. Blue is till, dark pink is glacifluvial deposits, green is moraine, and orange and yellow are older and younger alluvium respectively. See also Figure 27 for the other west-east aligned meltwater channels/reoccupied proto-Tees thalwegs.

Figure 32: NEXTMap DEM extract of the Woodland/Butterknowle upland and Langleydale showing axes of major moraine ridges (yellow dash lines) and eskers of the Woolly Hills (WH & green dash lines). Each ridge represents the location of former inter-ice stream moraine construction, presumably reflecting suture zone migration south of the limit of regional erratics. The Woolly Hills present a late stage re-entrant in the receding ice front. Meltwater drainage along the south facing slope of the Woodland/Butterknowle upland was directed by the downwasting margin of the ice over Langleydale, leading to the prominent incision of the Gaunless Valley. BWMB = ButterknowleWoodland Moraine Belt; CM = Cockfield Moraine.

Figure 33: Reconstructions of the sequentially younger stages of ice-marginal positions relating to the topographic confinement of glacier ice in Teesdale. The maximum northerly position of the full glacial ice stream suture zone is marked by the northern extent of regional erratics (thick blue line and blue arrows). The spillway and likely upper level of Glacial Lake Eggleshope are also marked. See Figure 18 for the locations and altitudes of landforms used in this reconstruction.

Figure 34: Reconstructed long profiles of increasingly topographically-confined ice lobes based upon the various inset latero-frontal moraines and associated landforms in central Teesdale. The full lateral and altitudinal extent of the moraine-dammed lake located up-valley of the Gueswick Moraine (blue shade) is unknown because its existence is documented only by the lowermost facies exposed at Hayberries.

Supplementary information

Figure 1: Map of the glacial geomorphology of Teesdale and adjacent areas overlain on NEXTMap imagery. This figure is best viewed at A1 paper size.

Click here to download high resolution image

Figure 1a

Click here to download high resolution image

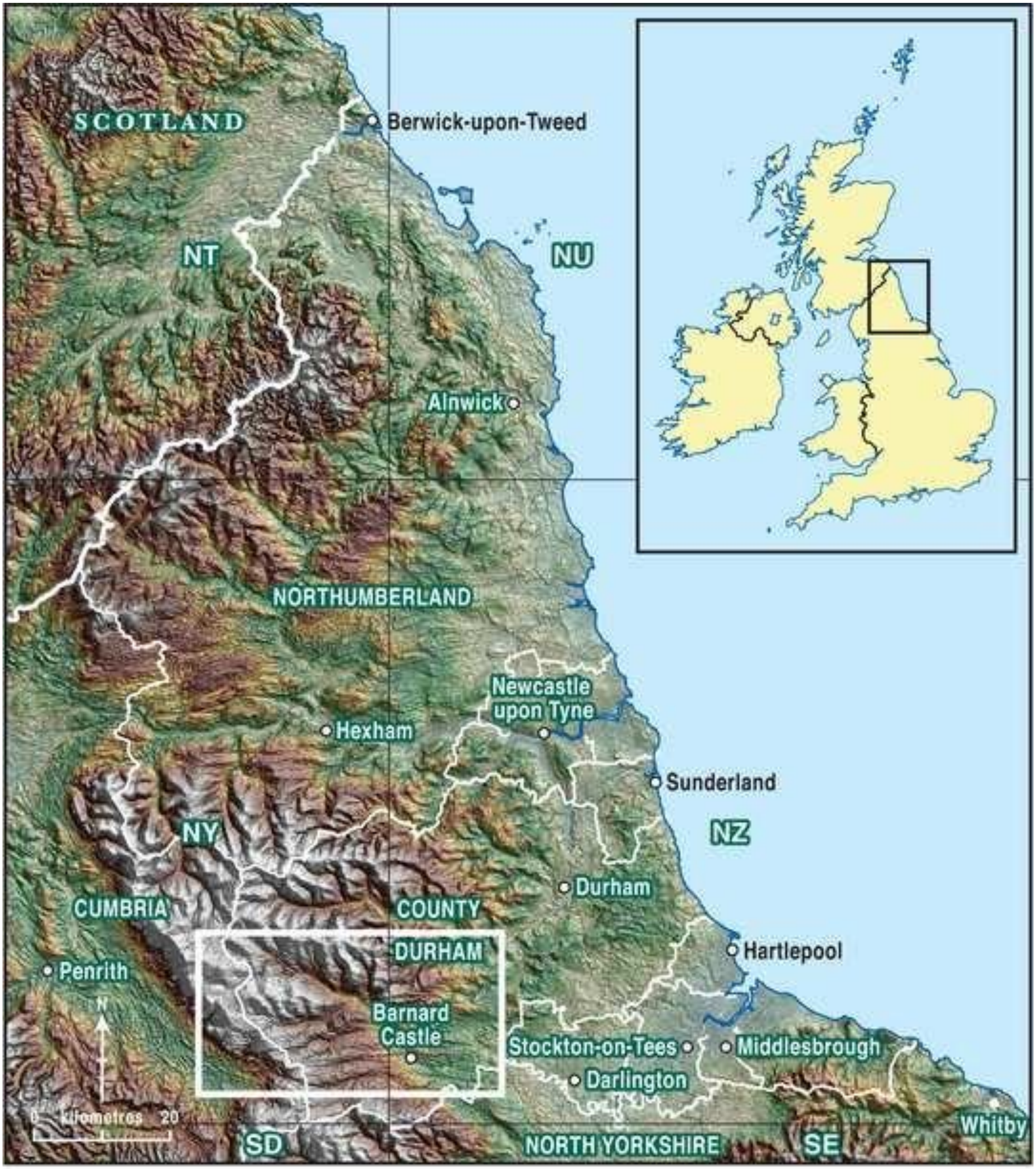


Figure 1b

Click here to download high resolution image

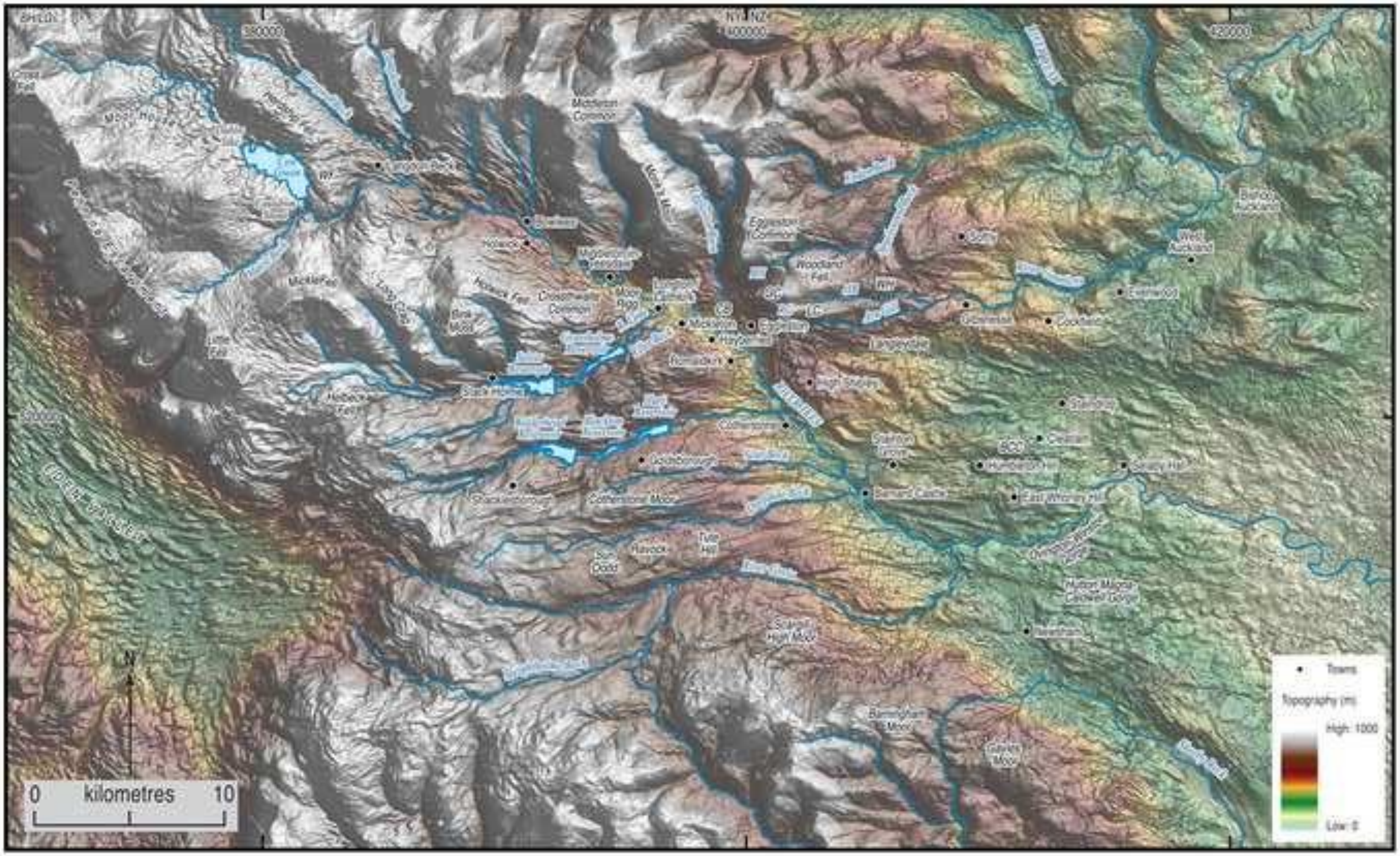


Figure 2
Click here to download high resolution image

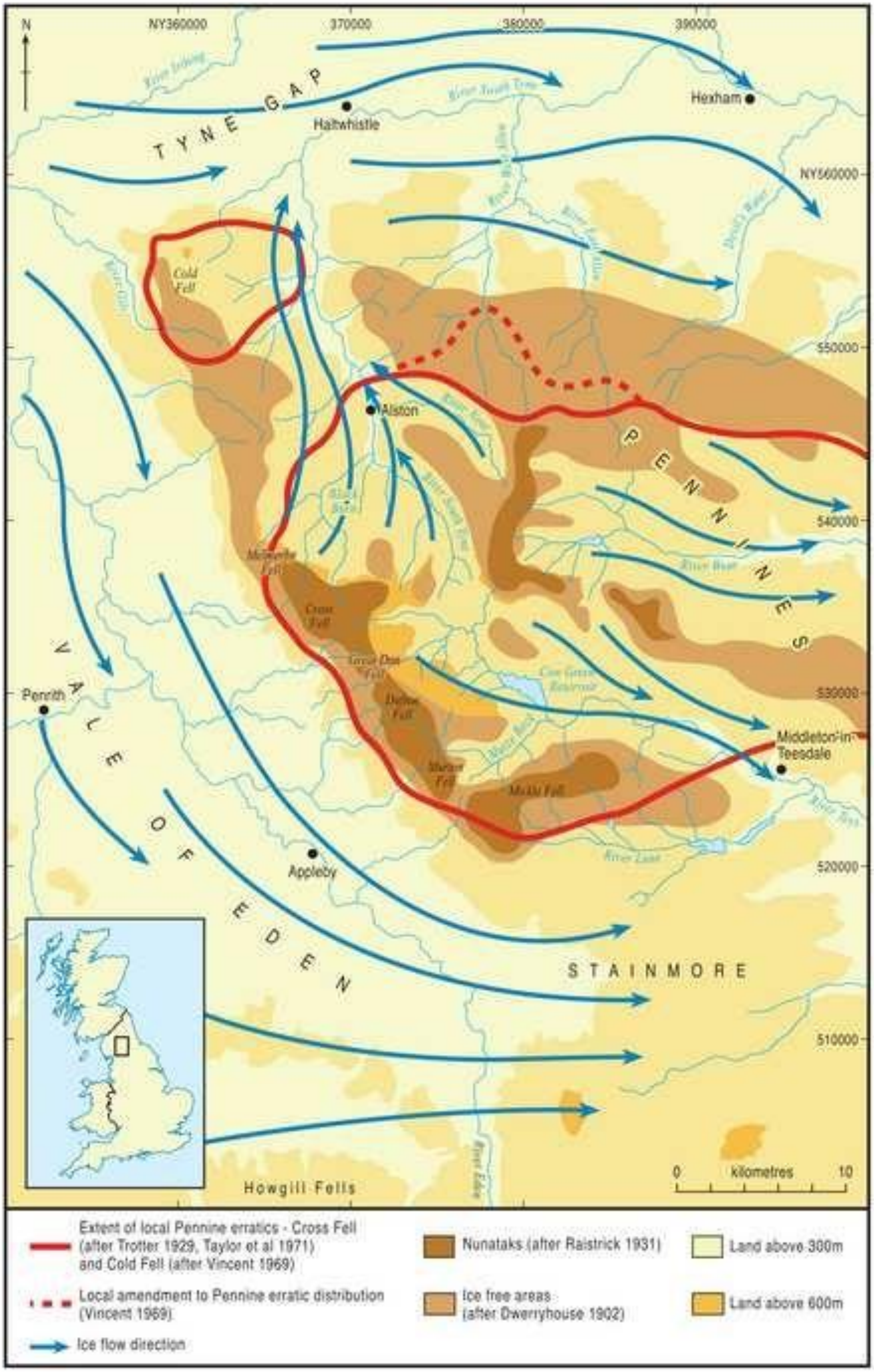


Figure 3
Click here to download high resolution image

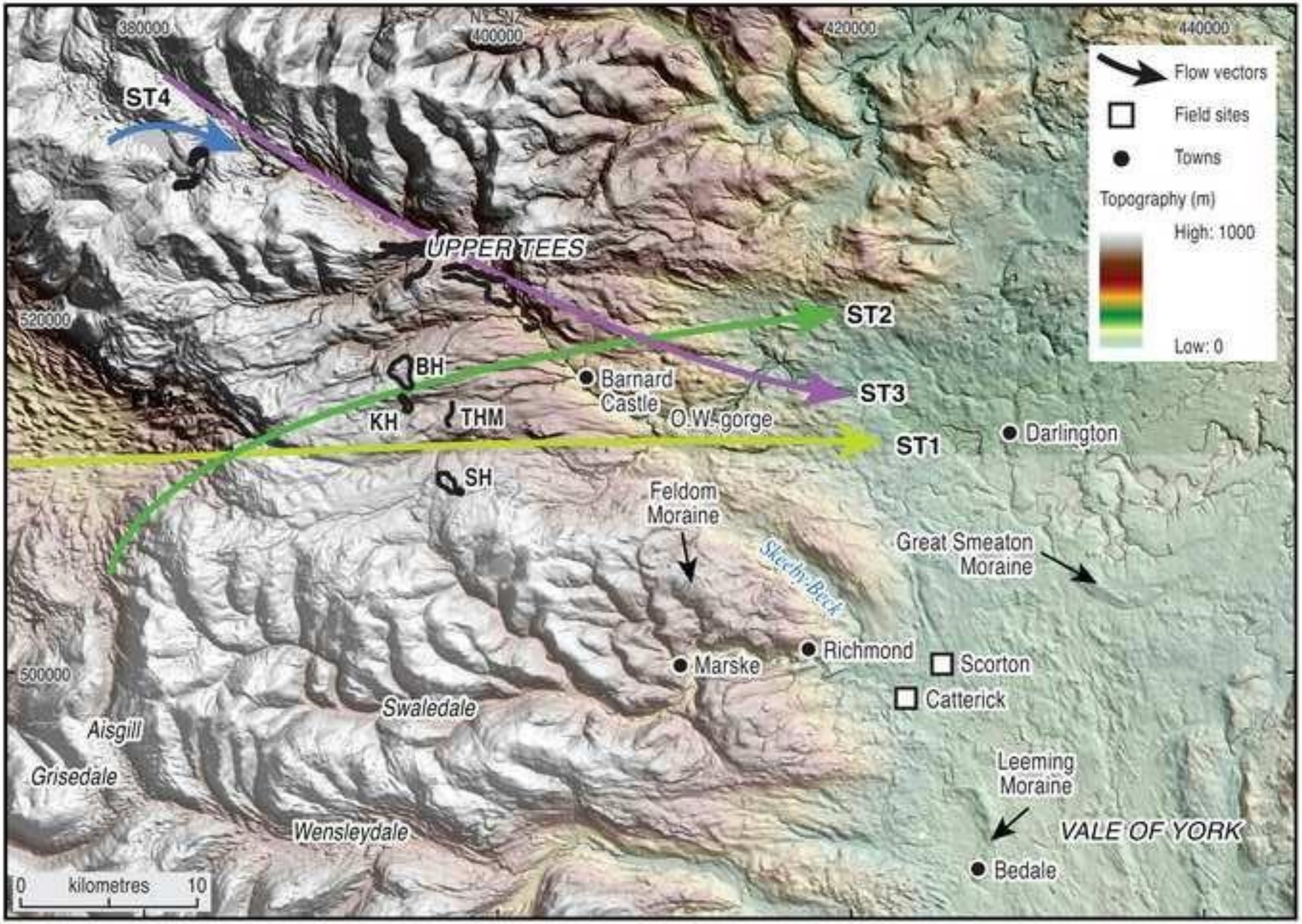


Figure 4

Click here to download high resolution image

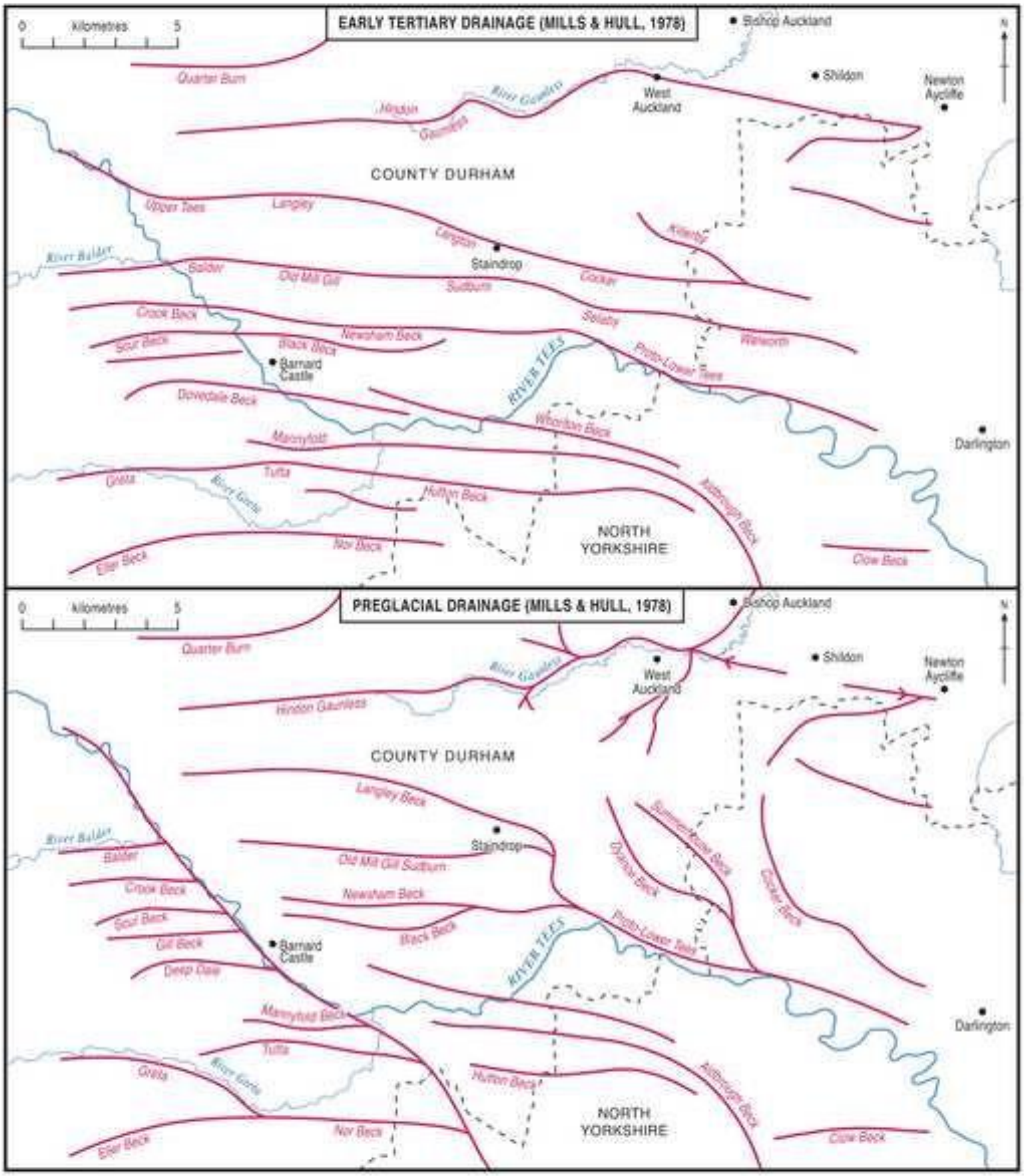


Figure 5
Click here to download high resolution image

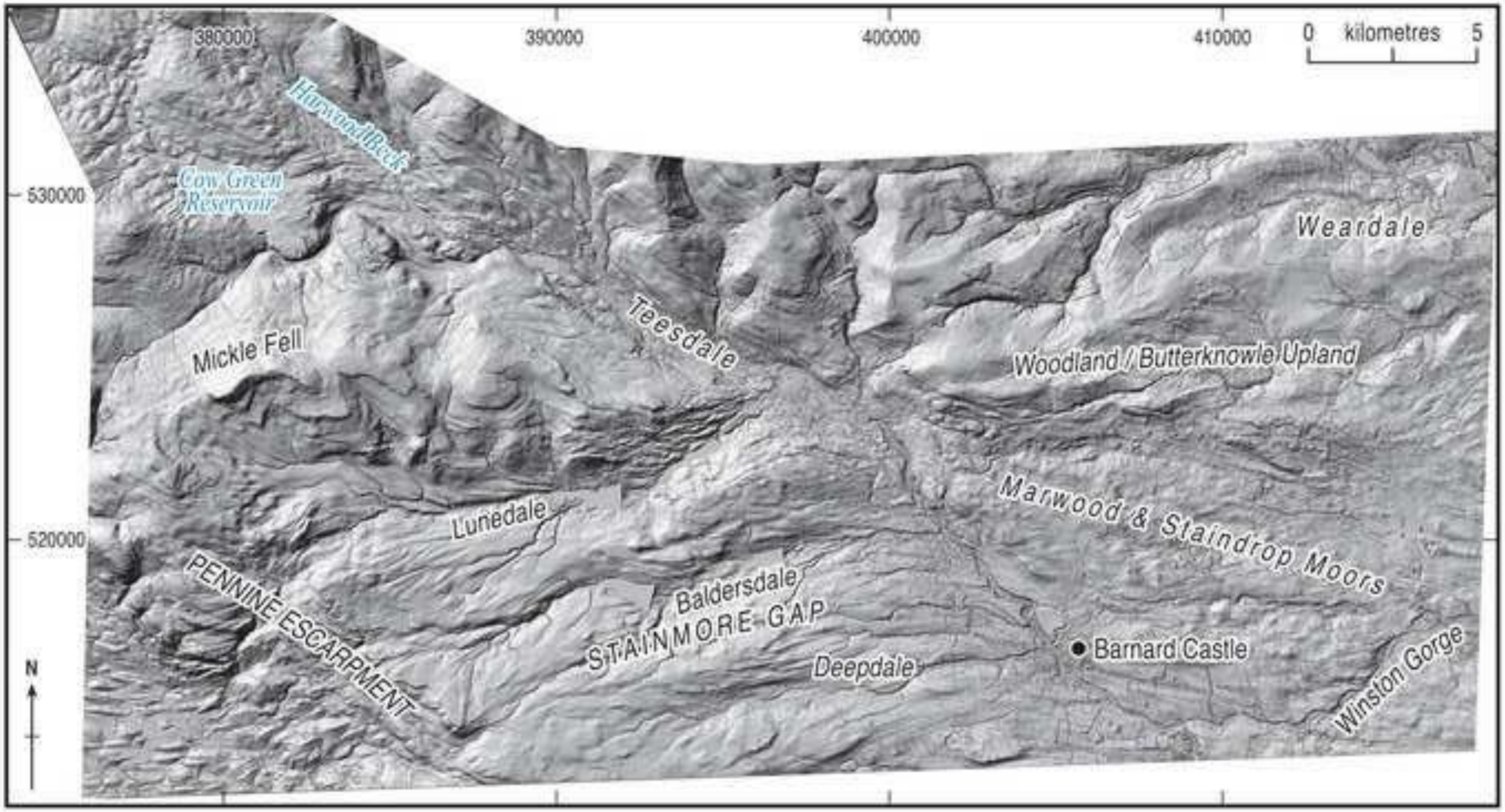


Figure 6a

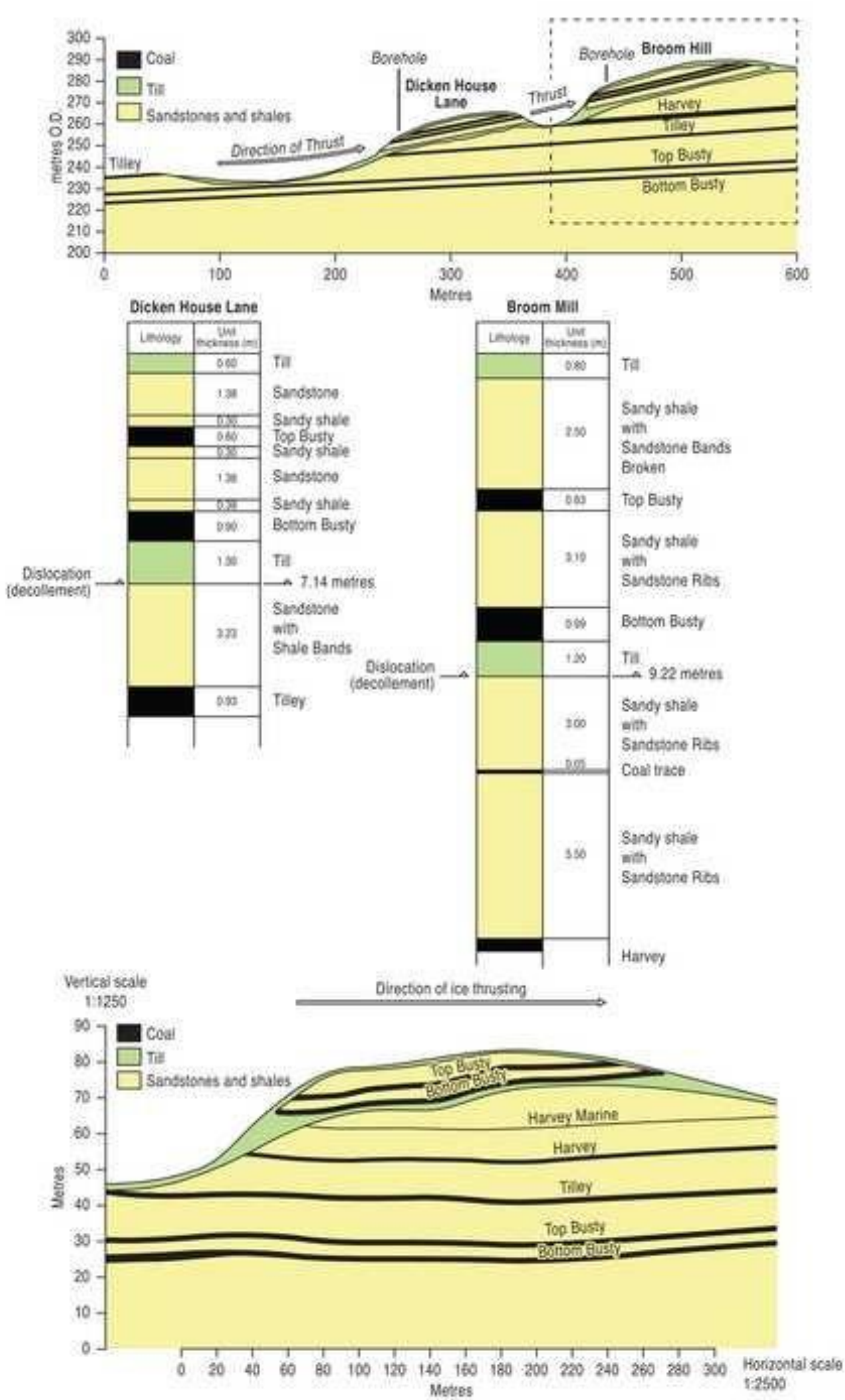

Coal
Till
Sandstones and shales
metres O.D.
Tilley
Direction of Thrust
Borehole
Dicken House Lane
Thrust
Borehole
Broom Hill
Harvey
Tilley
Top Busty
Bottom Busty
Metres
Dicken House Lane
Lithology
Unit thickness (m)
Till
Sandstone
Sandy shale
Top Busty
Sandy shale
Sandstone
Sandy shale
Bottom Busty
Till
Dislocation (decollement)
7.14 metres
Sandstone with Shale Bands
Tilley
Broom Mill
Lithology
Unit thickness (m)
Till
Sandy shale with Sandstone Bands Broken
Top Busty
Sandy shale with Sandstone Ribs
Bottom Busty
Till
Dislocation (decollement)
9.22 metres
Sandy shale with Sandstone Ribs
Coal trace
Sandy shale with Sandstone Ribs
Harvey
Vertical scale 1:1250
Direction of ice thrusting
Coal
Till
Sandstones and shales
Metres
Top Busty
Bottom Busty
Harvey Marine
Harvey
Tilley
Top Busty
Bottom Busty
Metres
Horizontal scale 1:2500

Figure 7
Click here to download high resolution image

Figure 6b

Click here to download high resolution image

Figure 9
Click here to download high resolution image

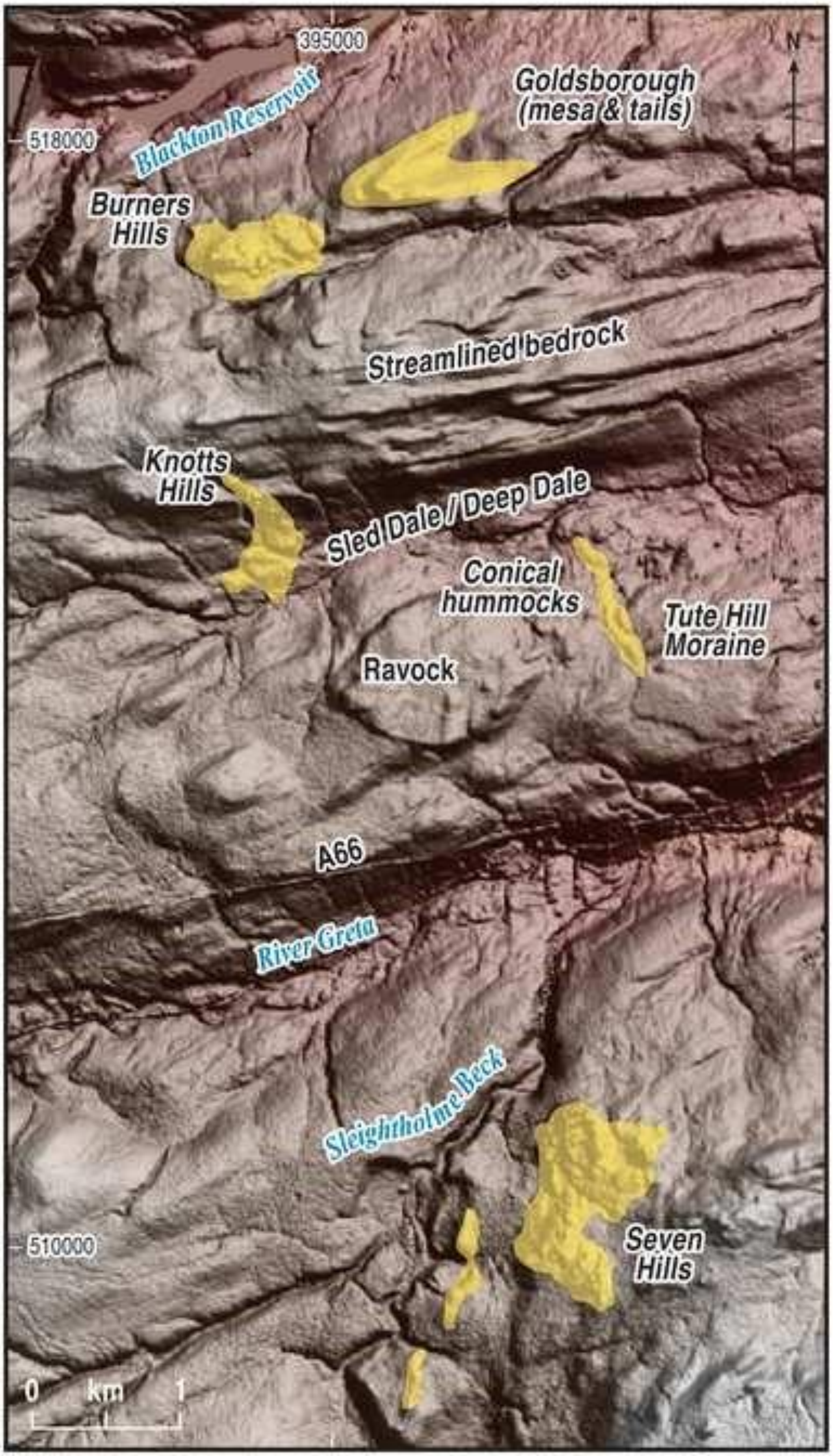


Figure 10
Click here to download high resolution image

Figure 11
Click here to download high resolution image

Figure 12
Click here to download high resolution image

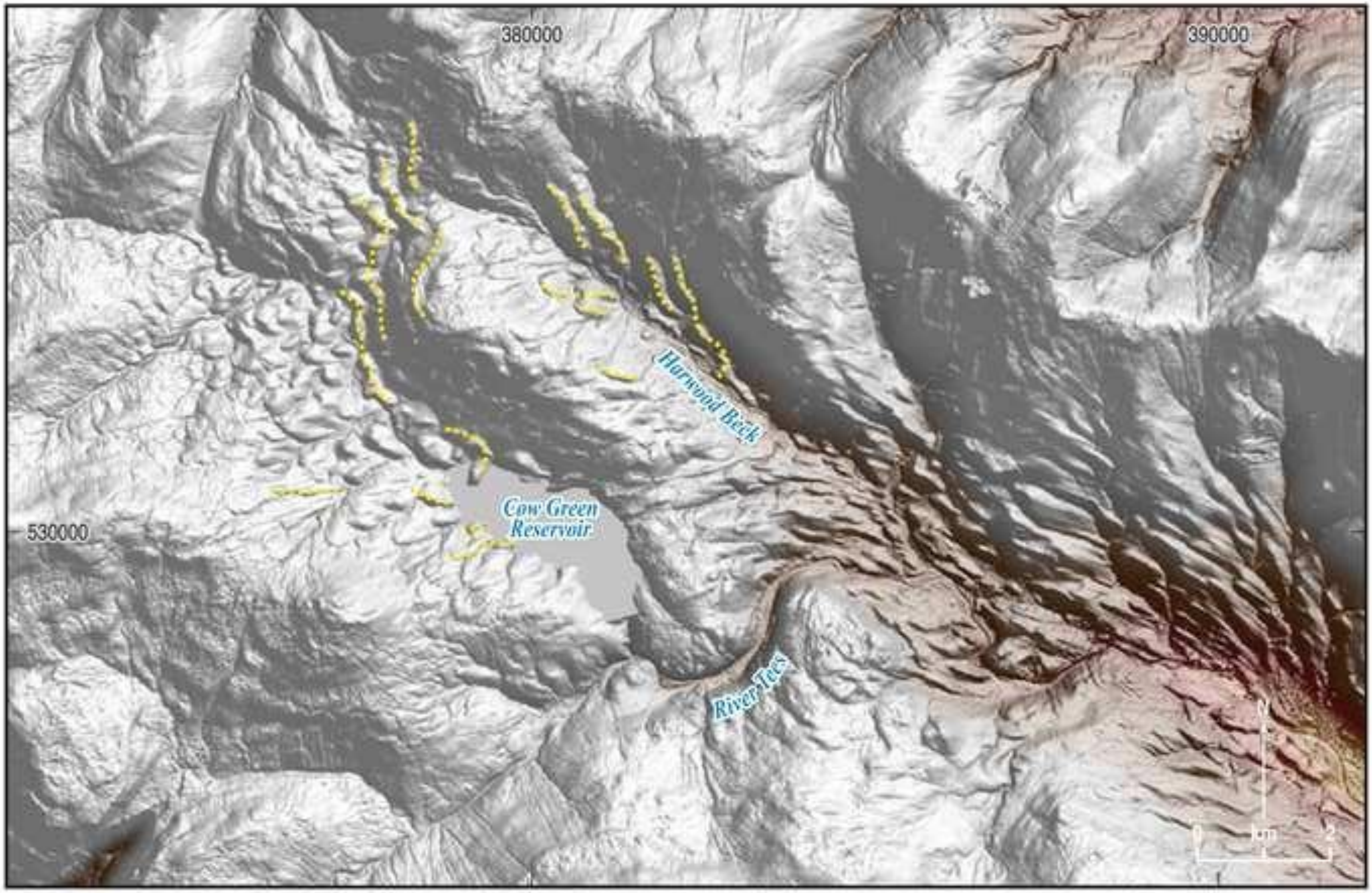


Figure 13

Click here to download high resolution image

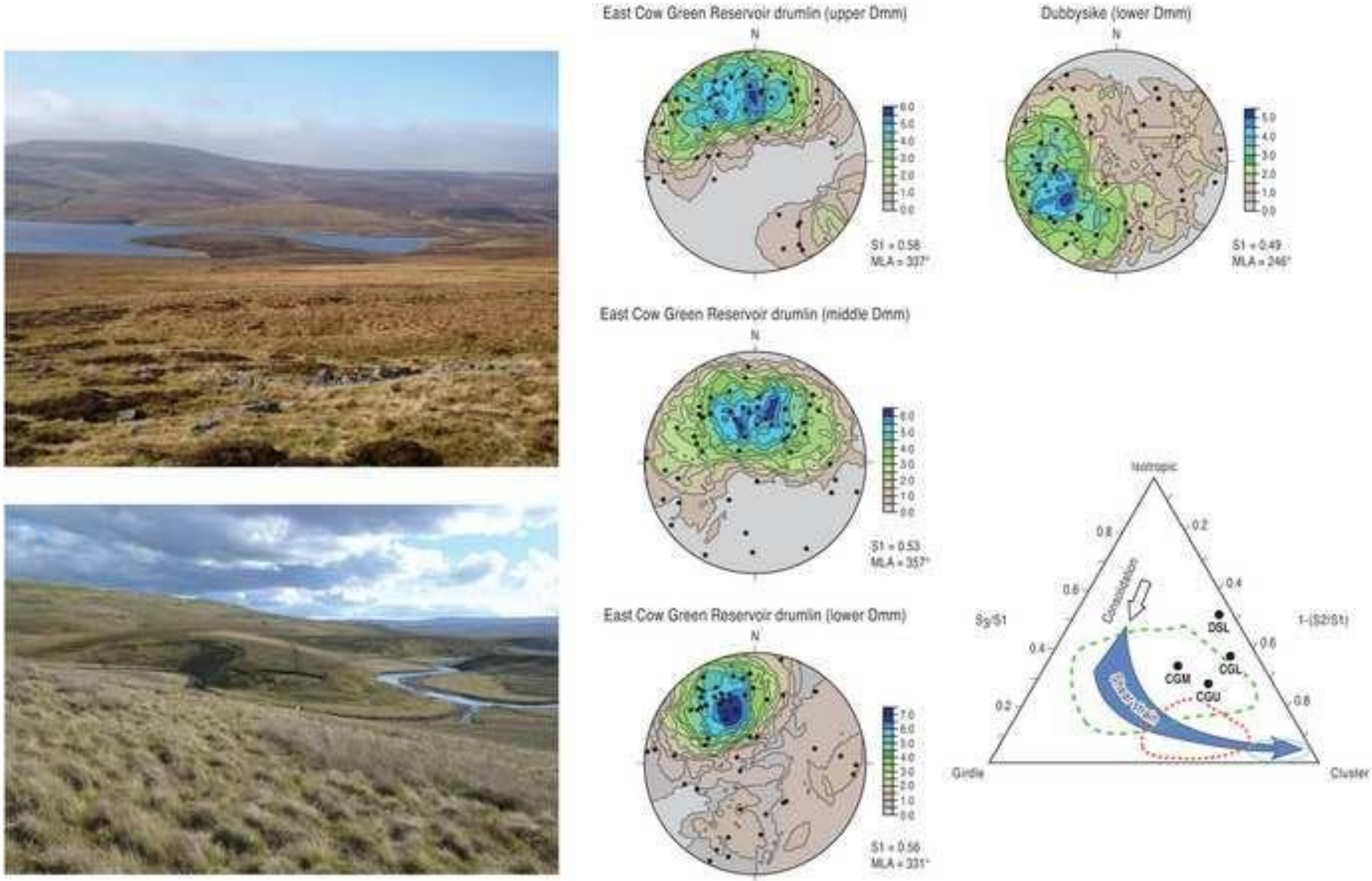


Figure 14
Click here to download high resolution image

Figure 15
Click here to download high resolution image

Figure 16
Click here to download high resolution image

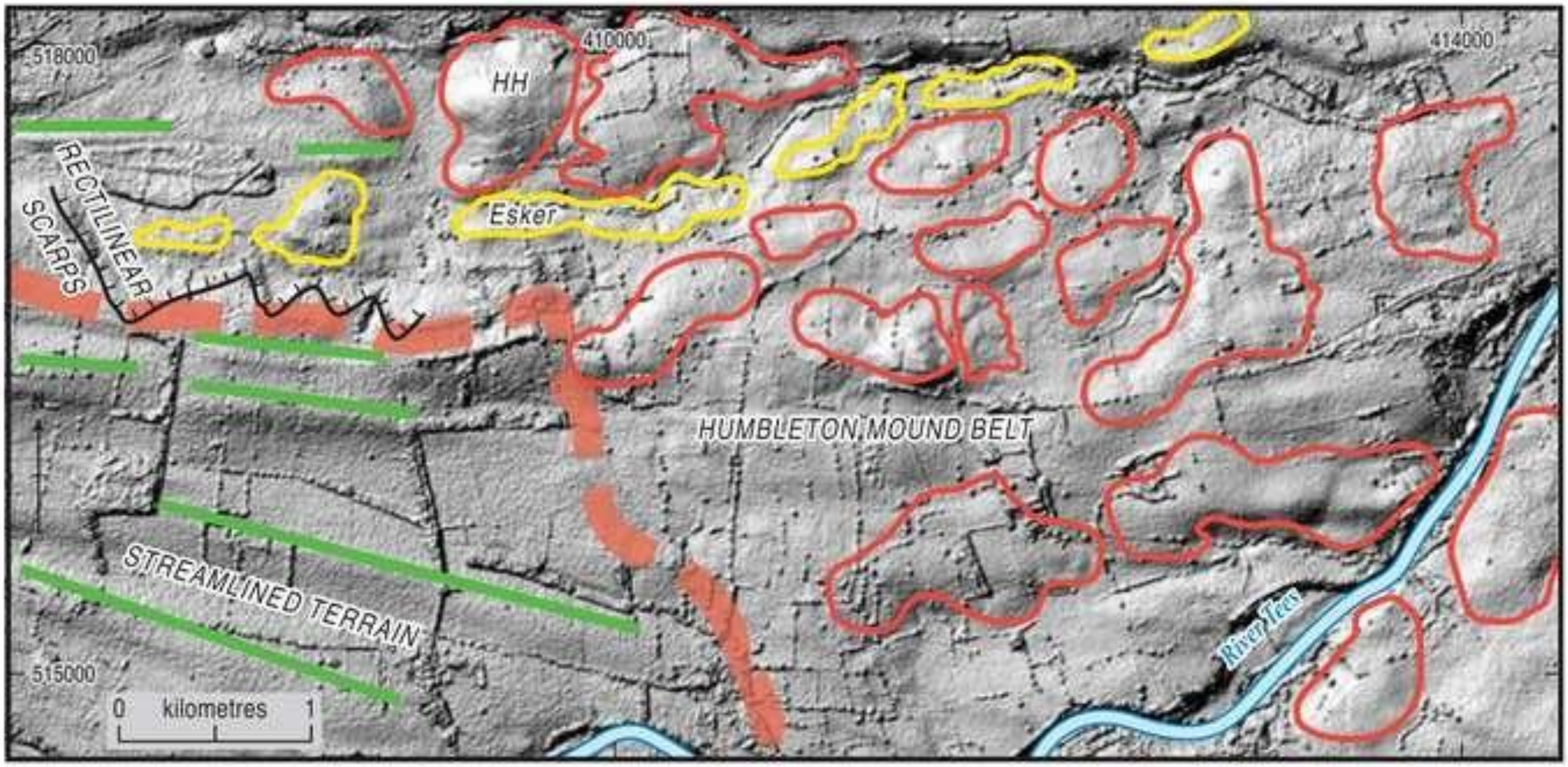


Figure 17
Click here to download high resolution image

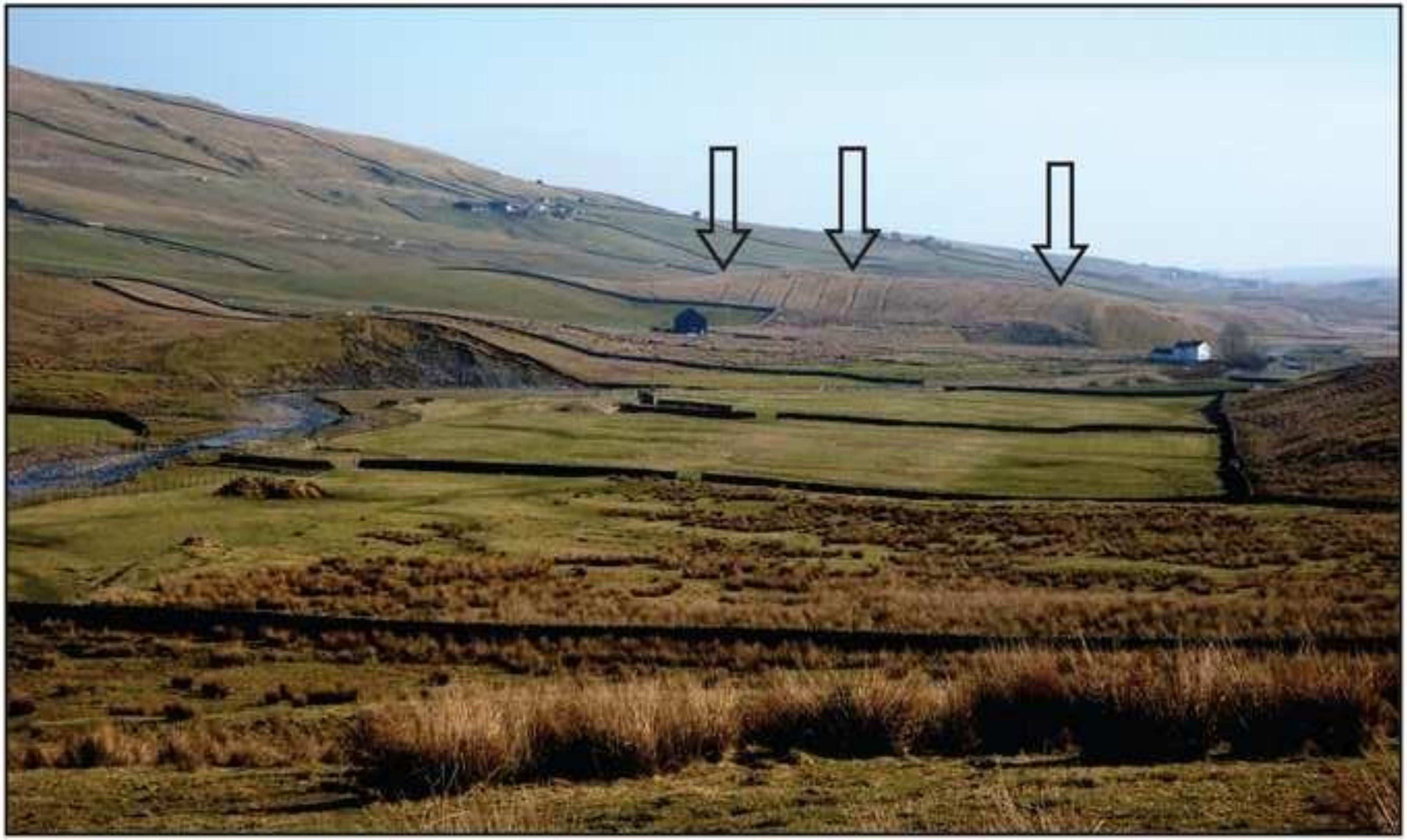


Figure 18
Click here to download high resolution image

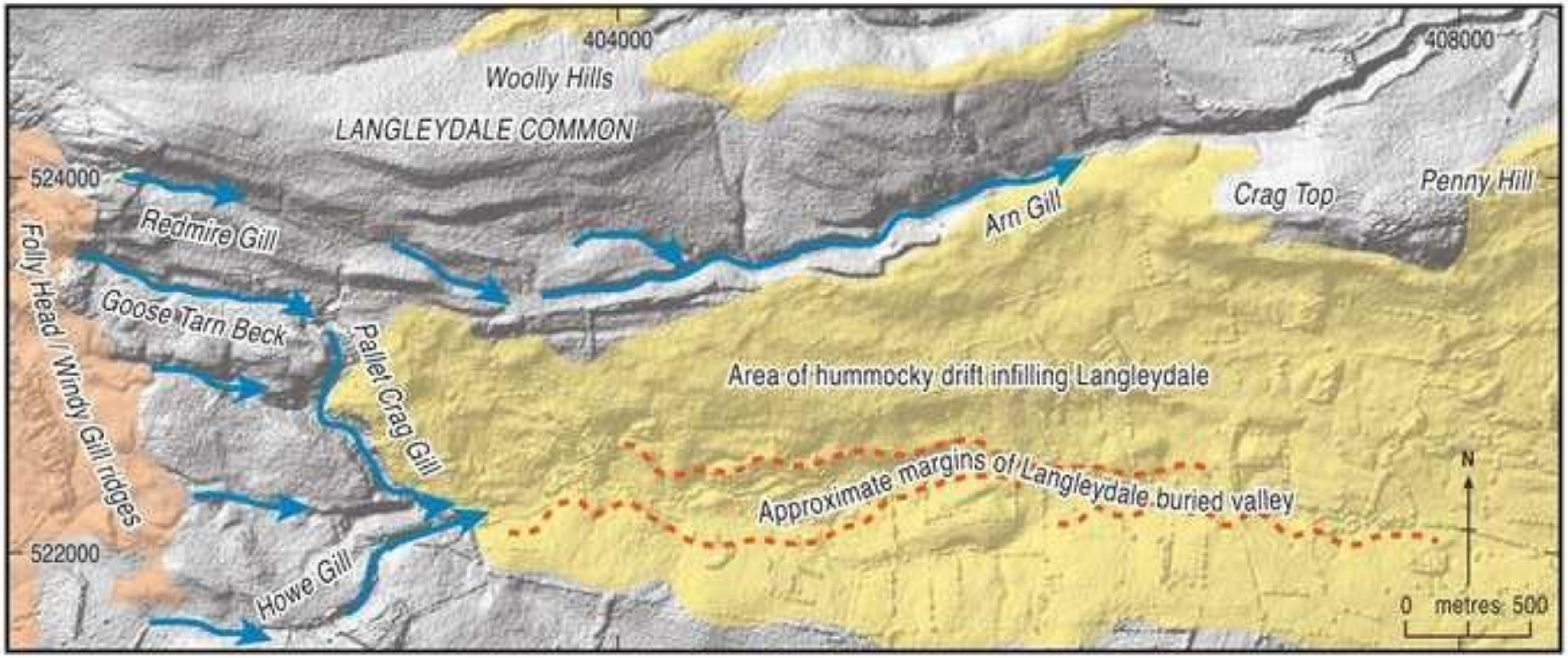


Figure 19
Click here to download high resolution image

Figure 20

Click here to download high resolution image

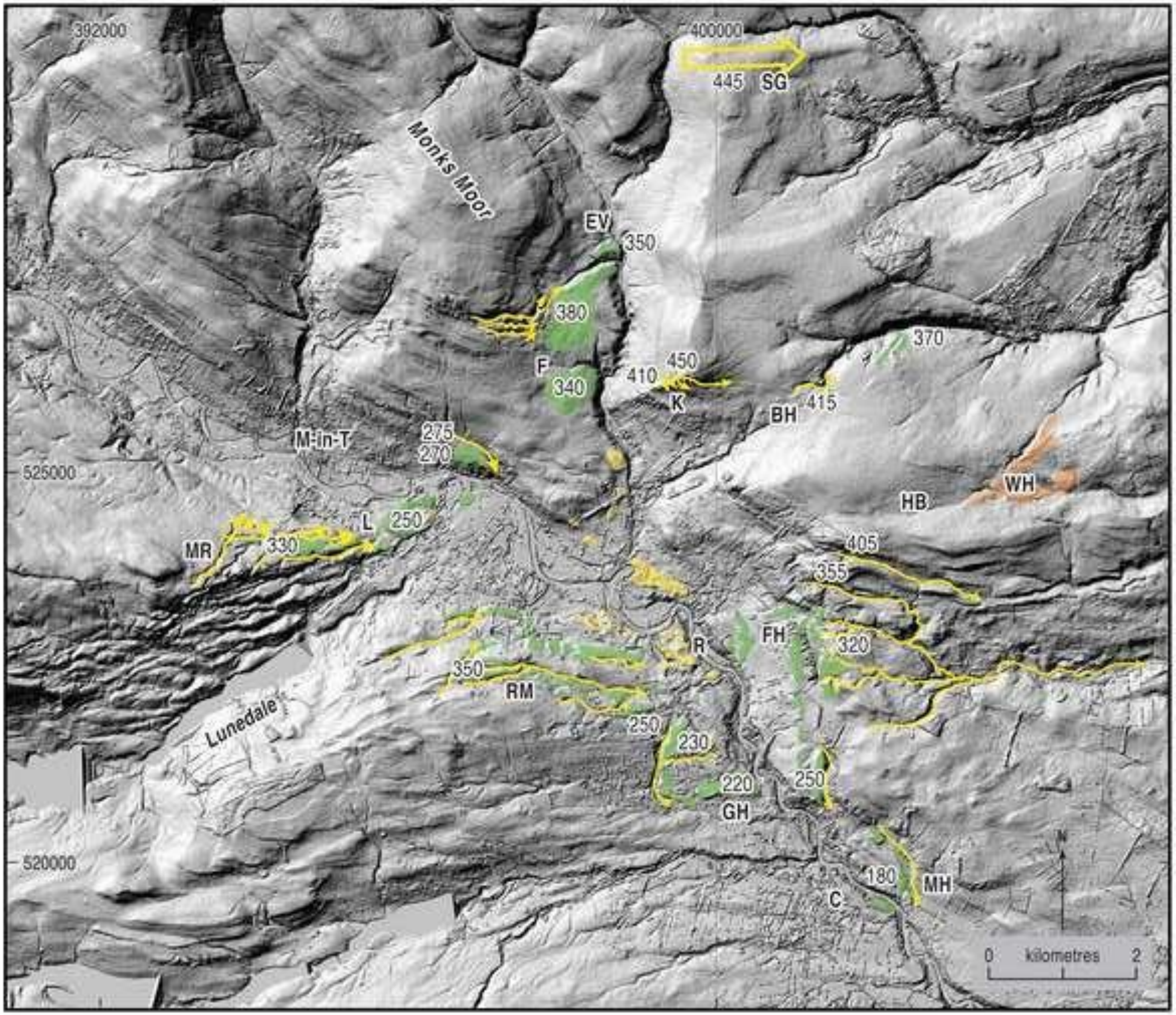


Figure 21
Click here to download high resolution image

Figure 22
Click here to download high resolution image

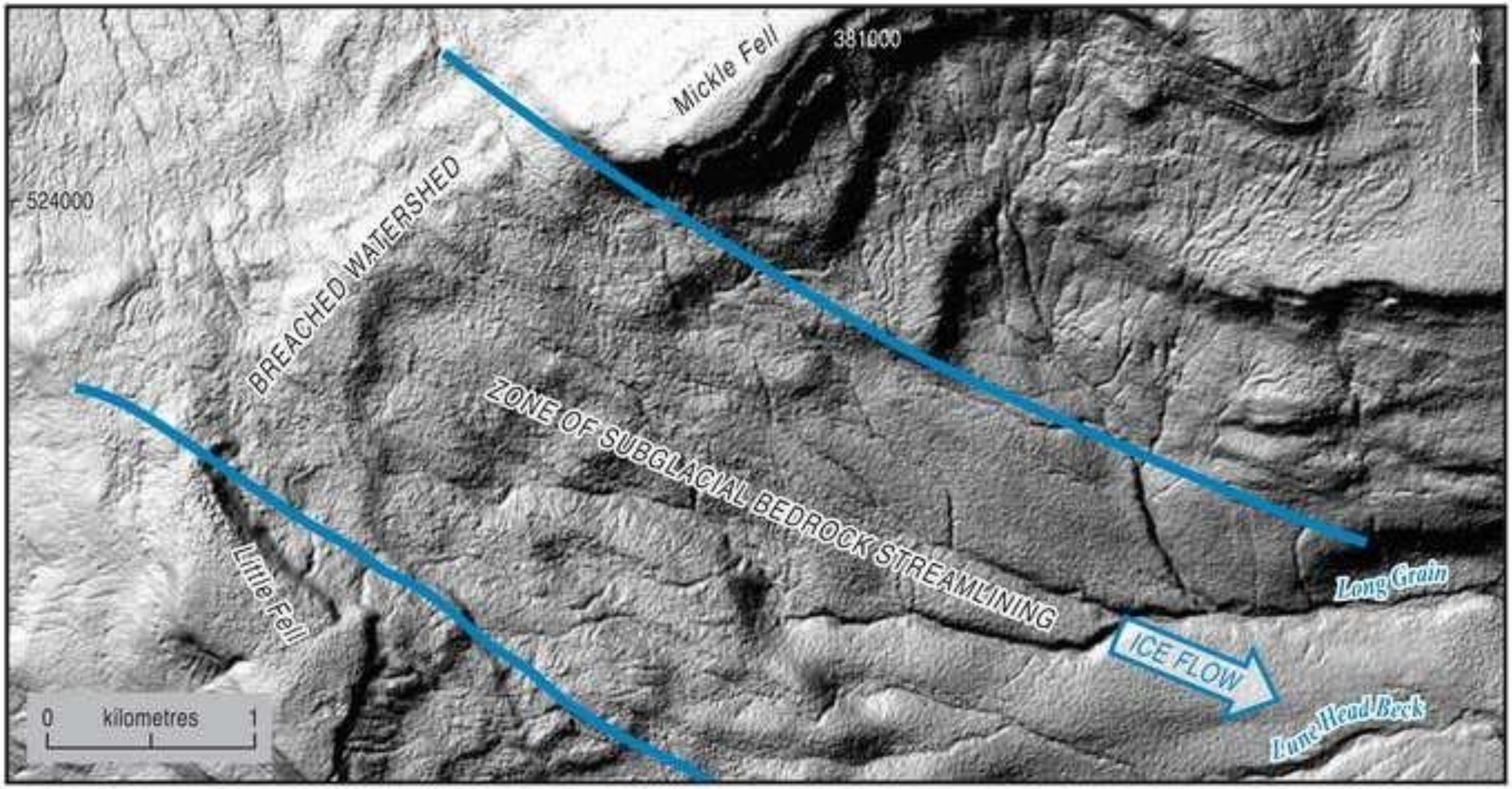


Figure 23
Click here to download high resolution image

Figure 22a

Click here to download high resolution image

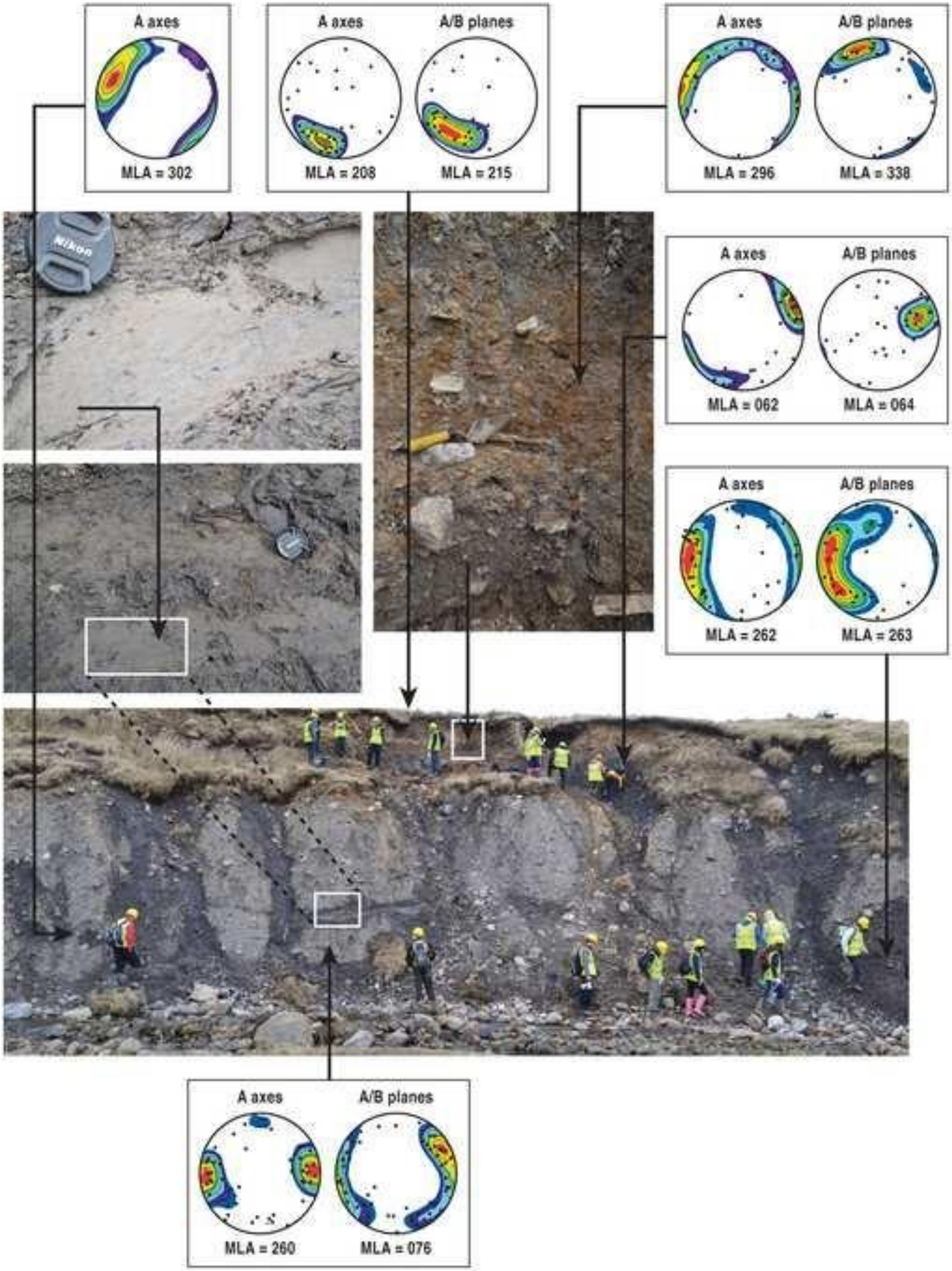


Figure 22b
Click here to download high resolution image

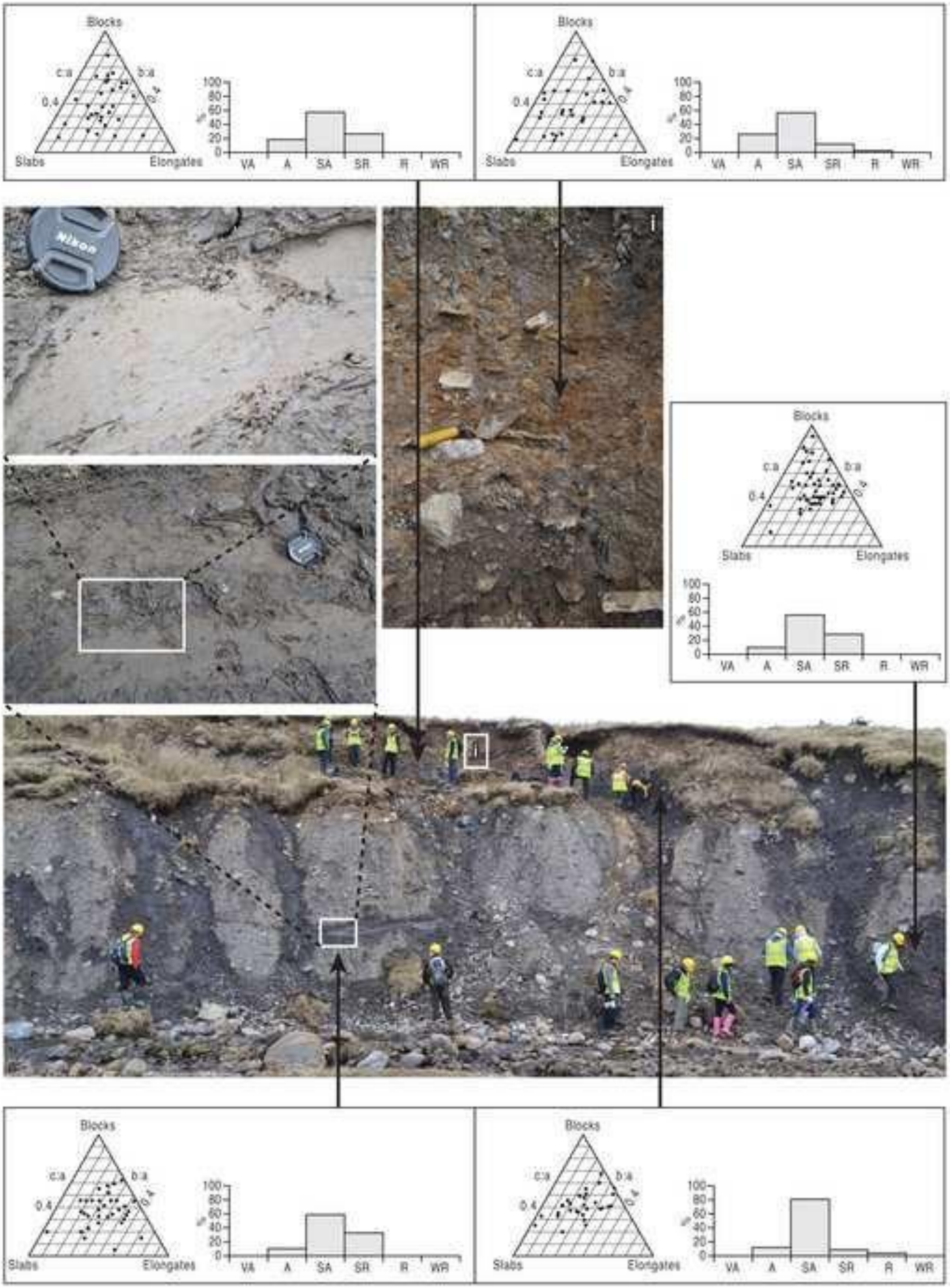
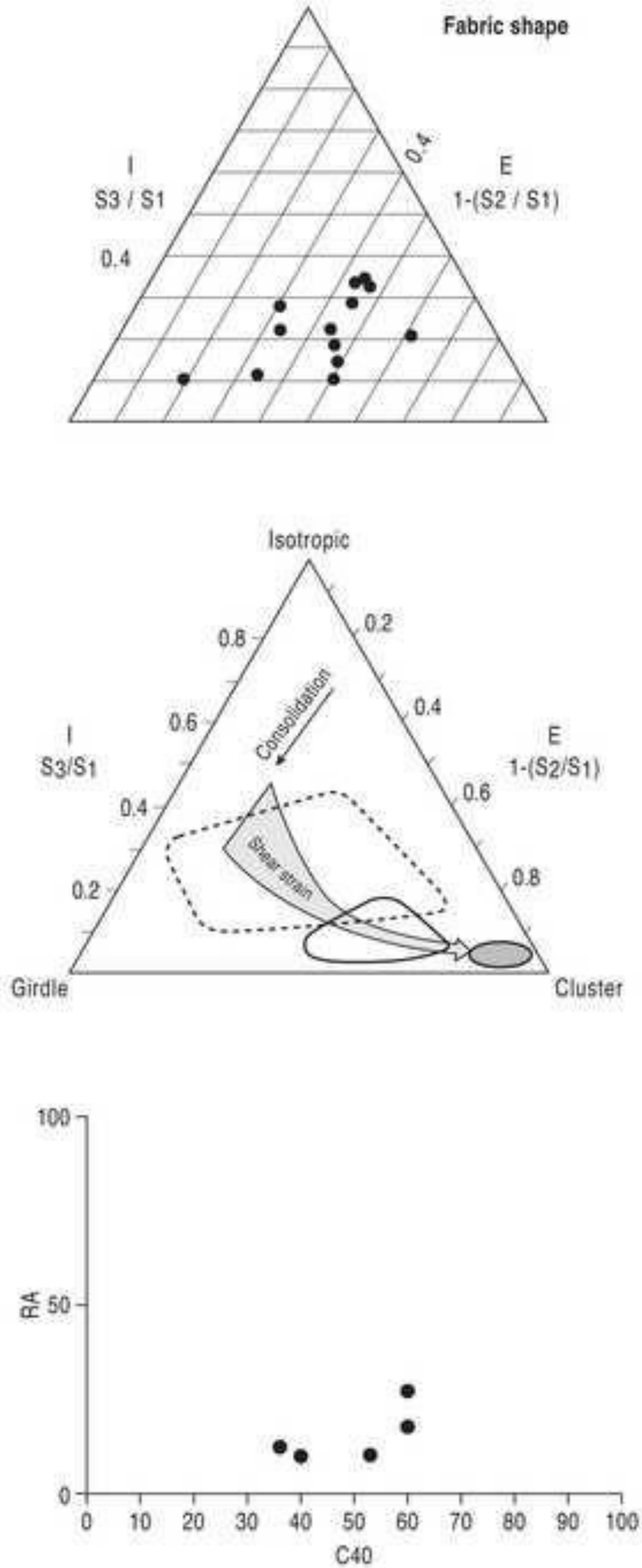


Figure 22c

Click here to download high resolution image



Click here to download high resolution image

Figure 23

Click here to download high resolution image

Click here to download high resolution image

Figure 24

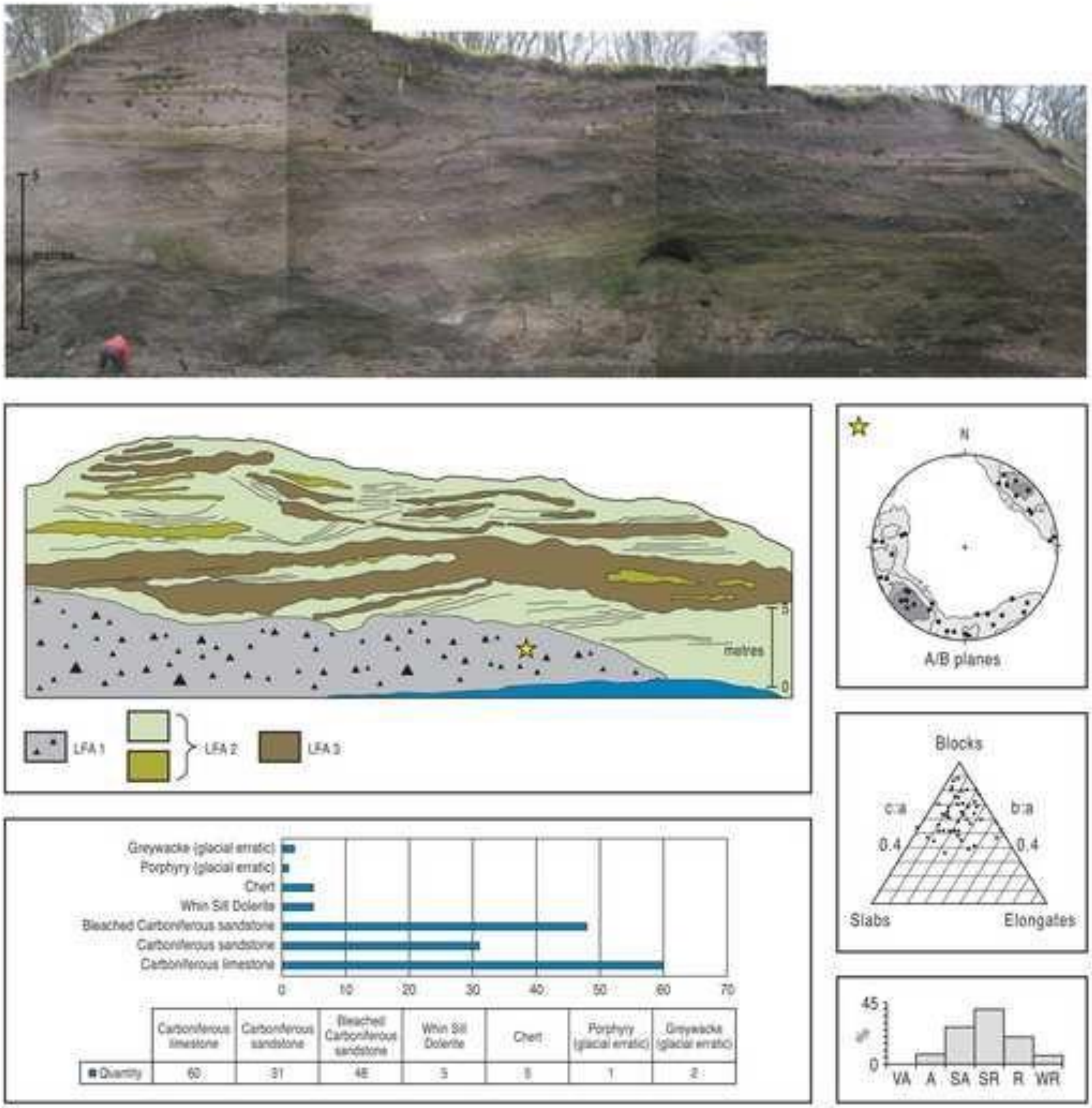
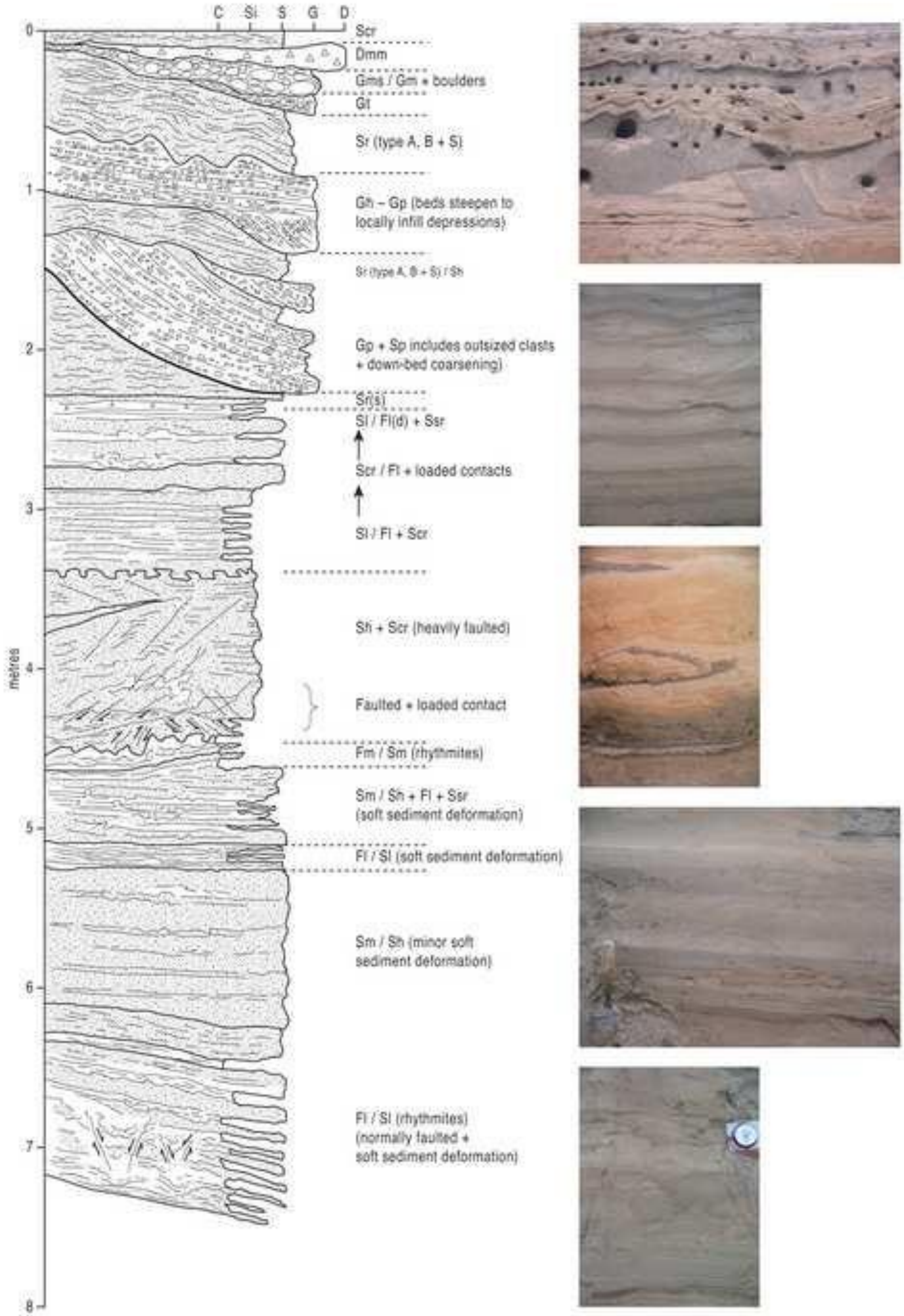


Figure 25a

Click here to download high resolution image



Click here to download high resolution image

Figure 25b

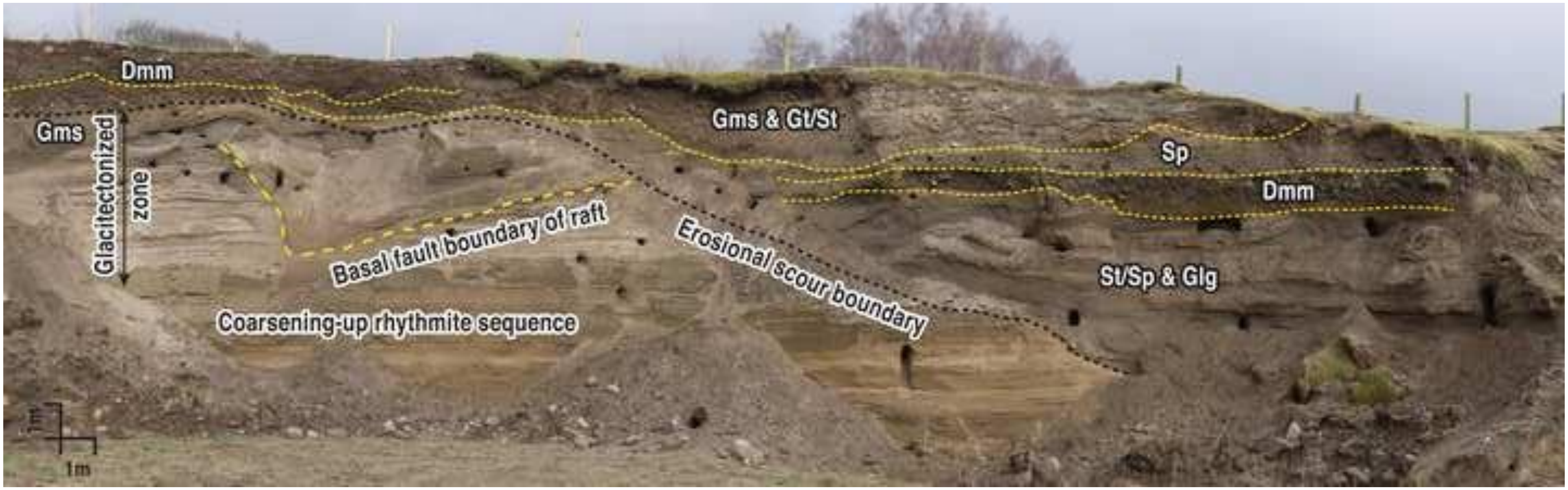


Figure 26

Click here to download high resolution image

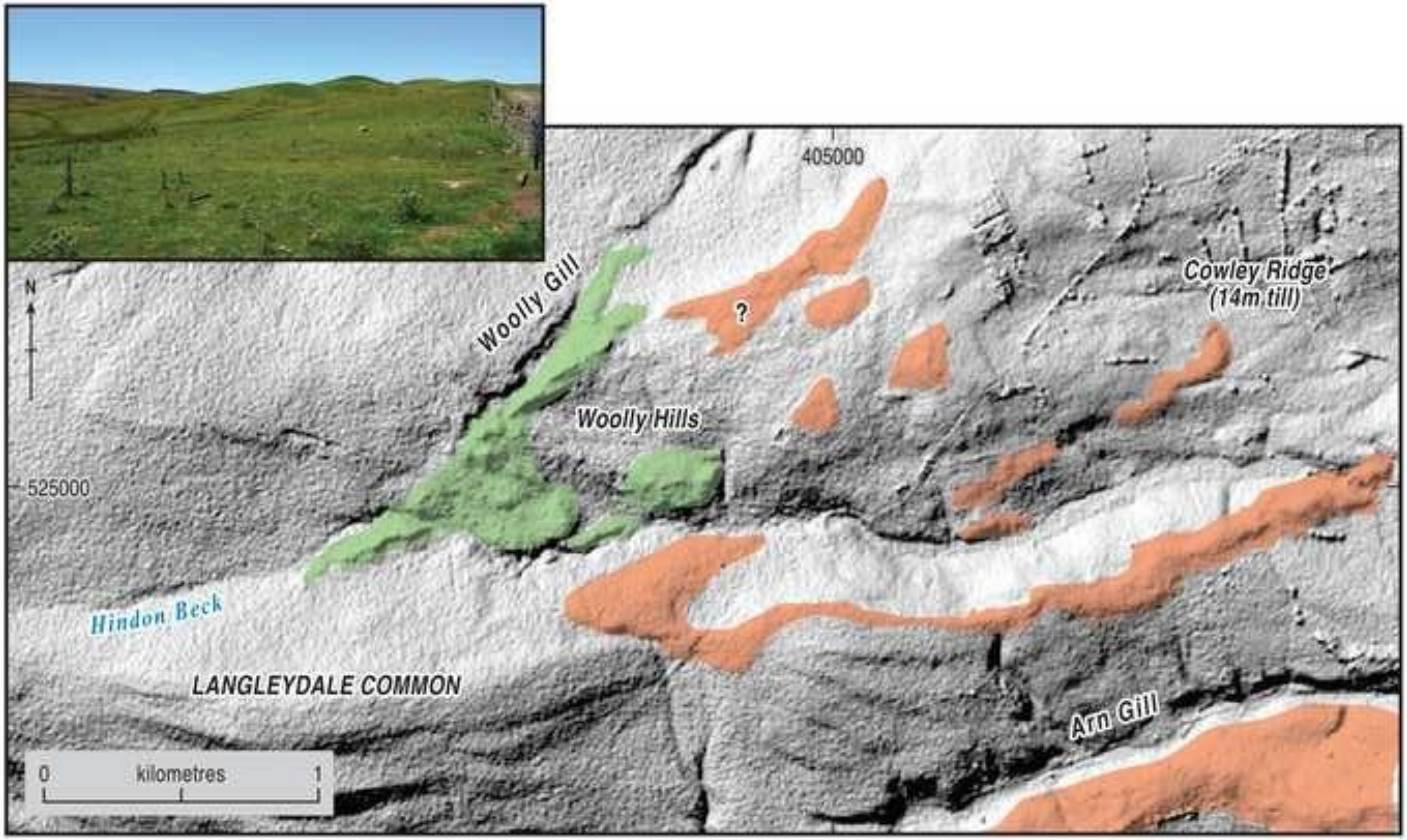


Figure 27

Click here to download high resolution image

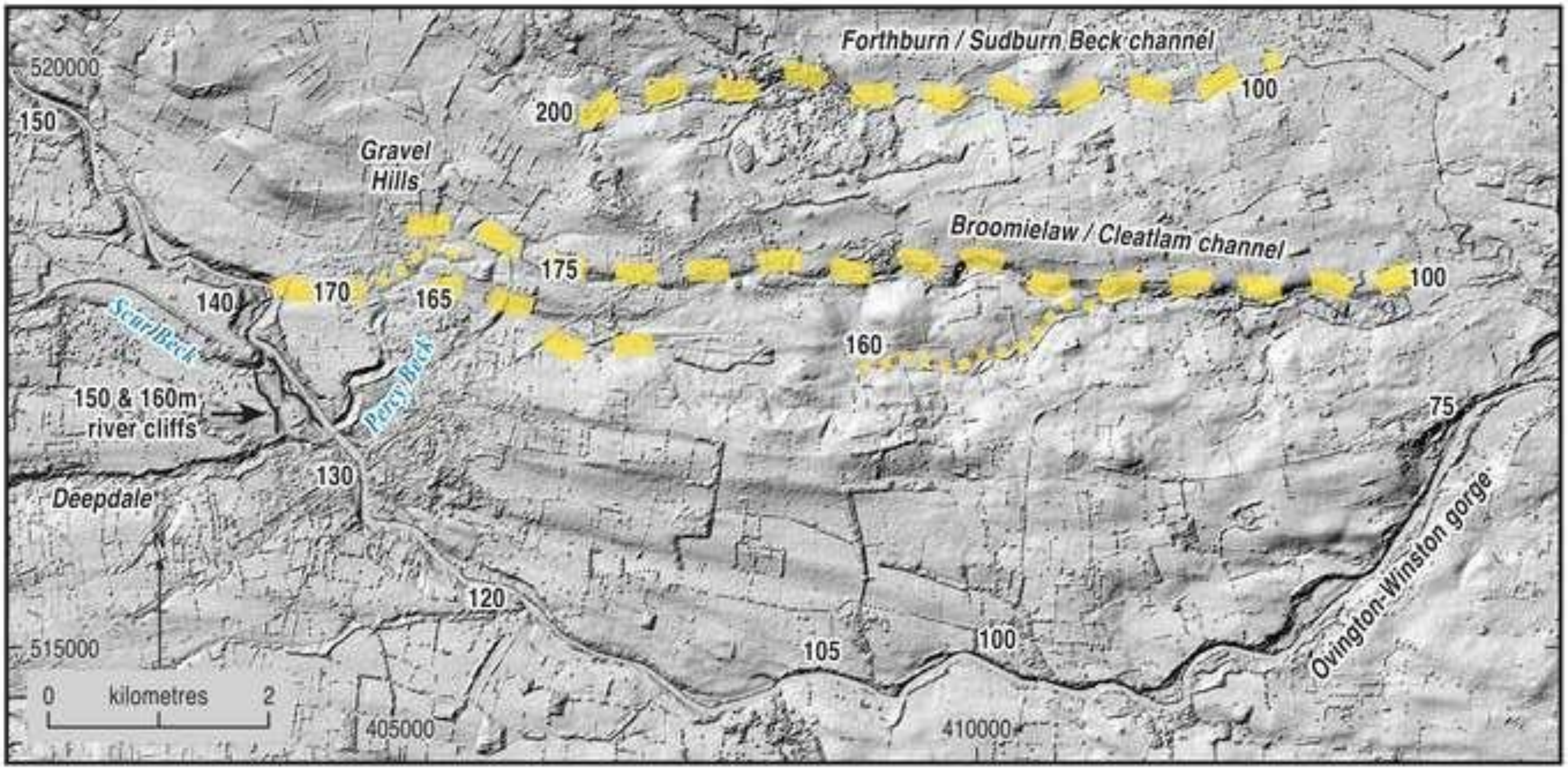


Figure 28a
Click here to download high resolution image

Figure 28b

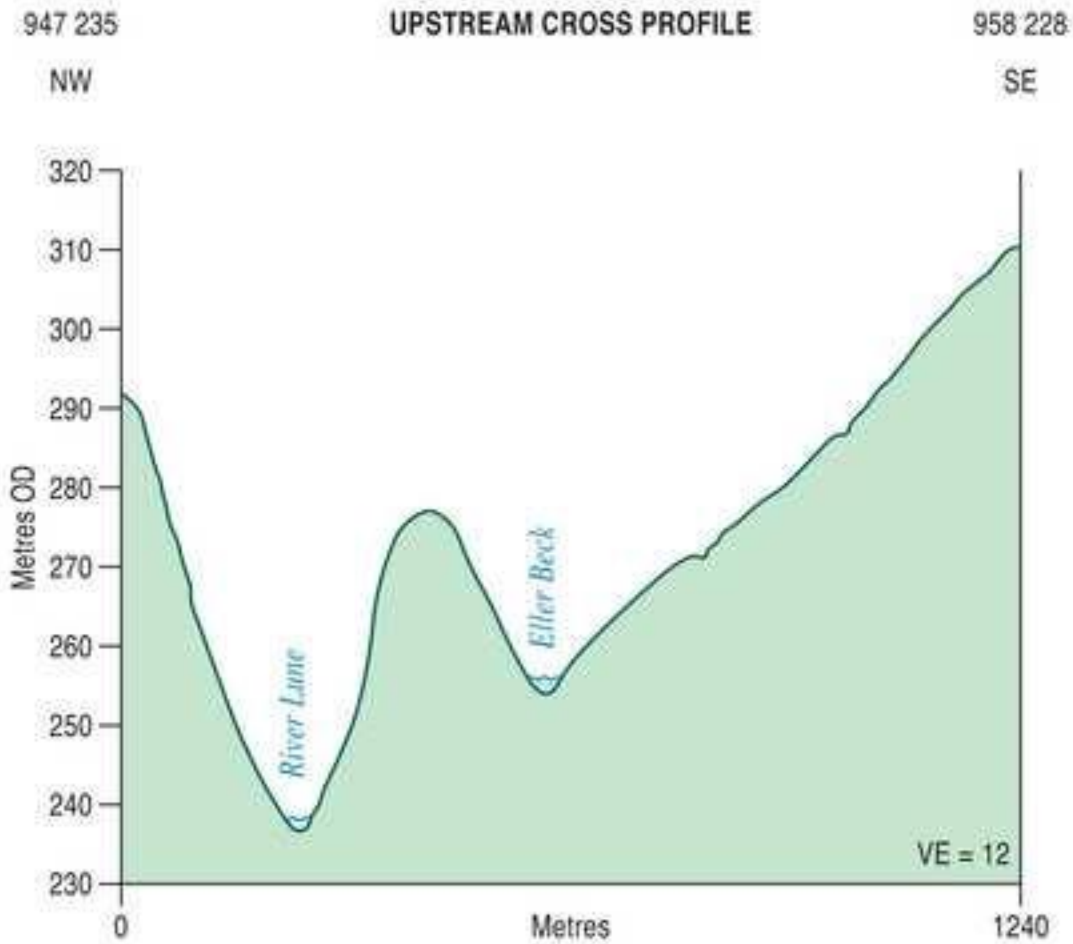
Click here to download high resolution image

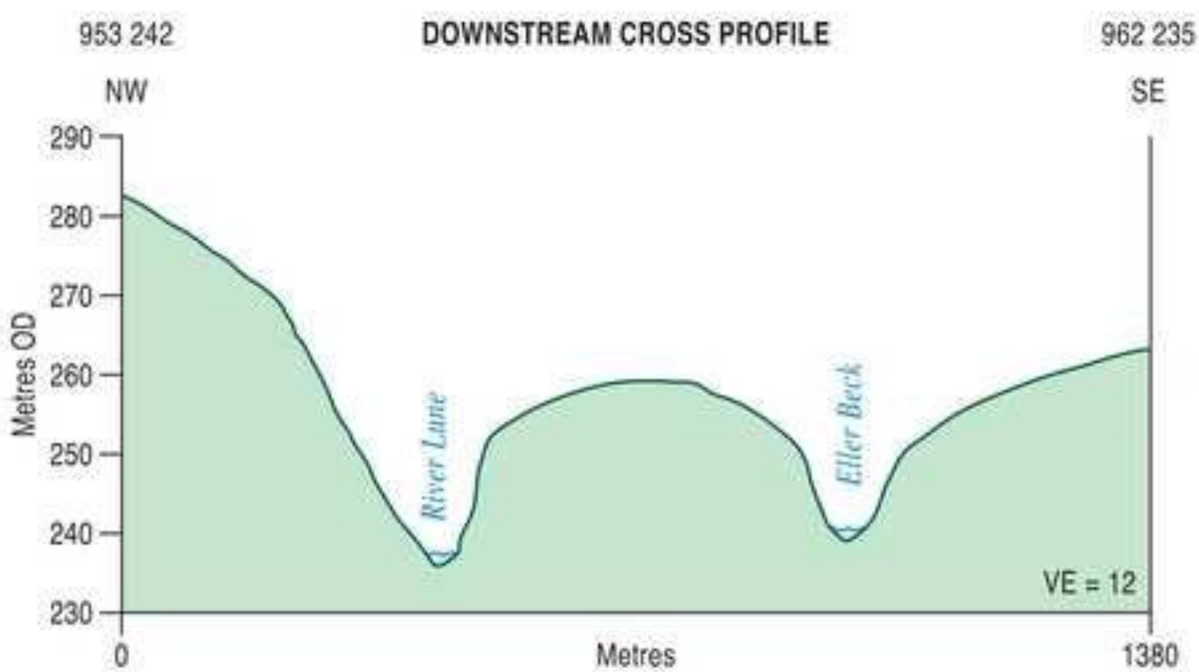
Figure 28c
Click here to download high resolution image

Click here to download high resolution image

Figure 29a

Click here to download high resolution image





Click here to download high resolution image

Figure 29b

Figure 30

Click here to download high resolution image

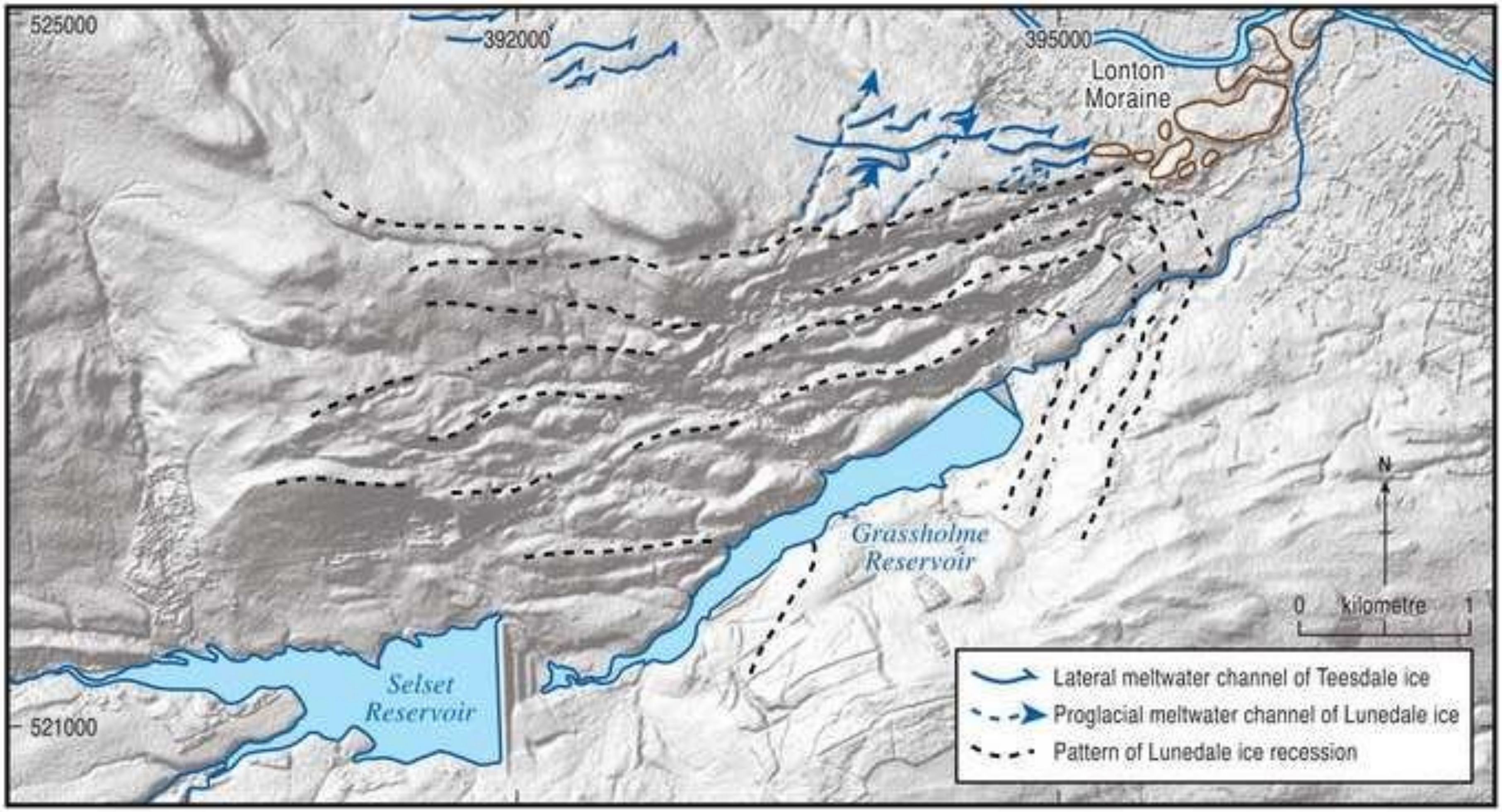


Figure 31
Click here to download high resolution image

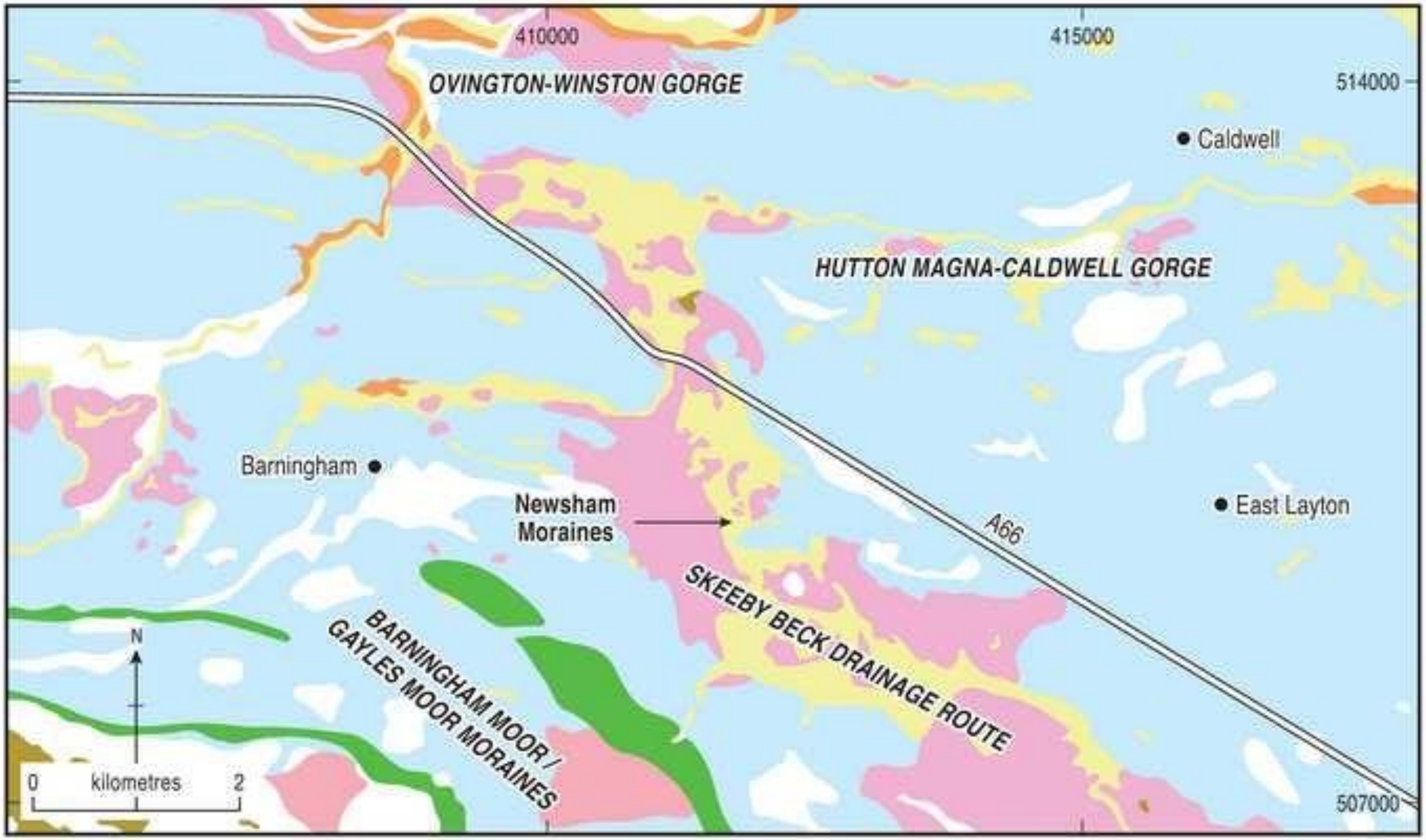


Figure 32
Click here to download high resolution image

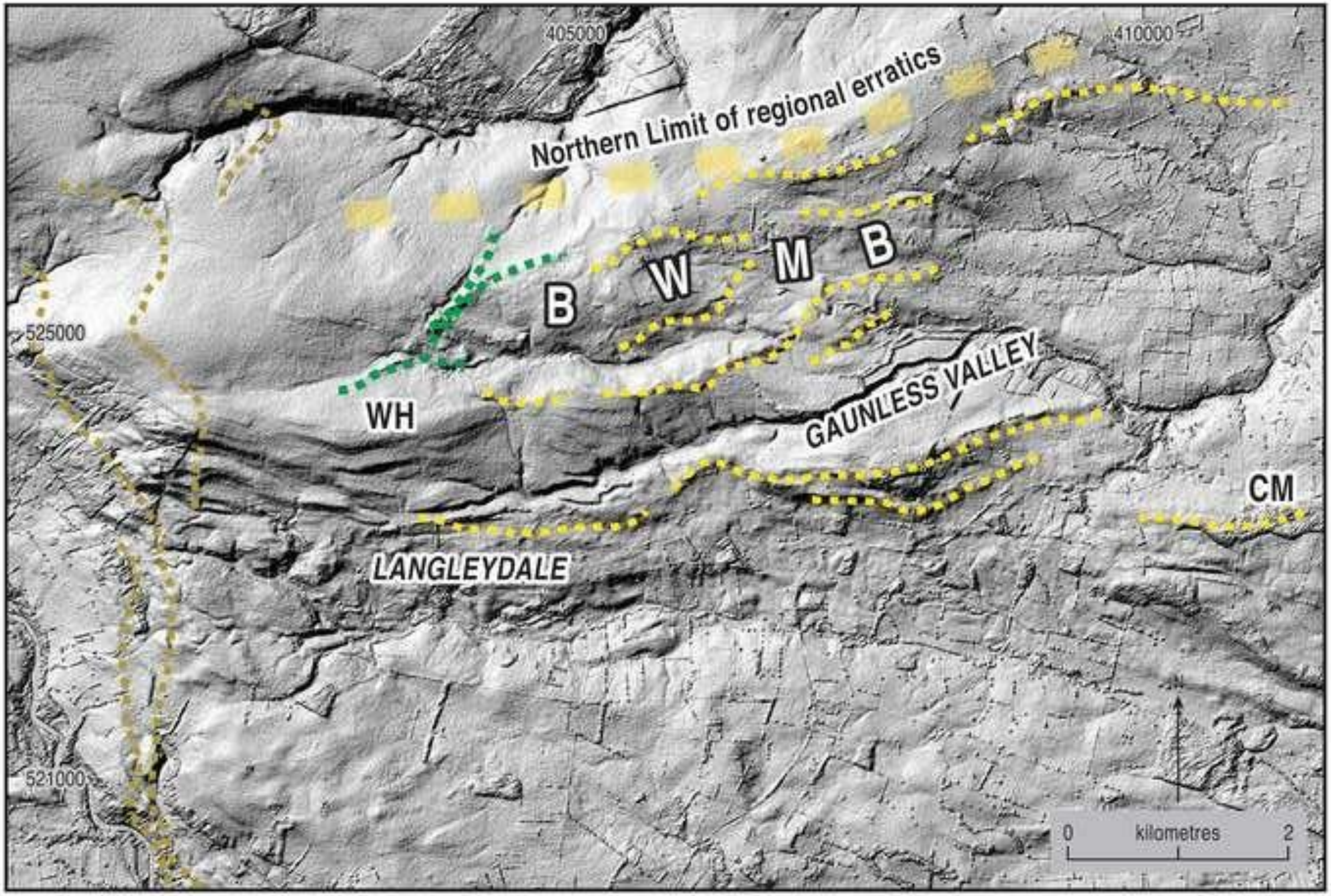


Figure 33
Click here to download high resolution image

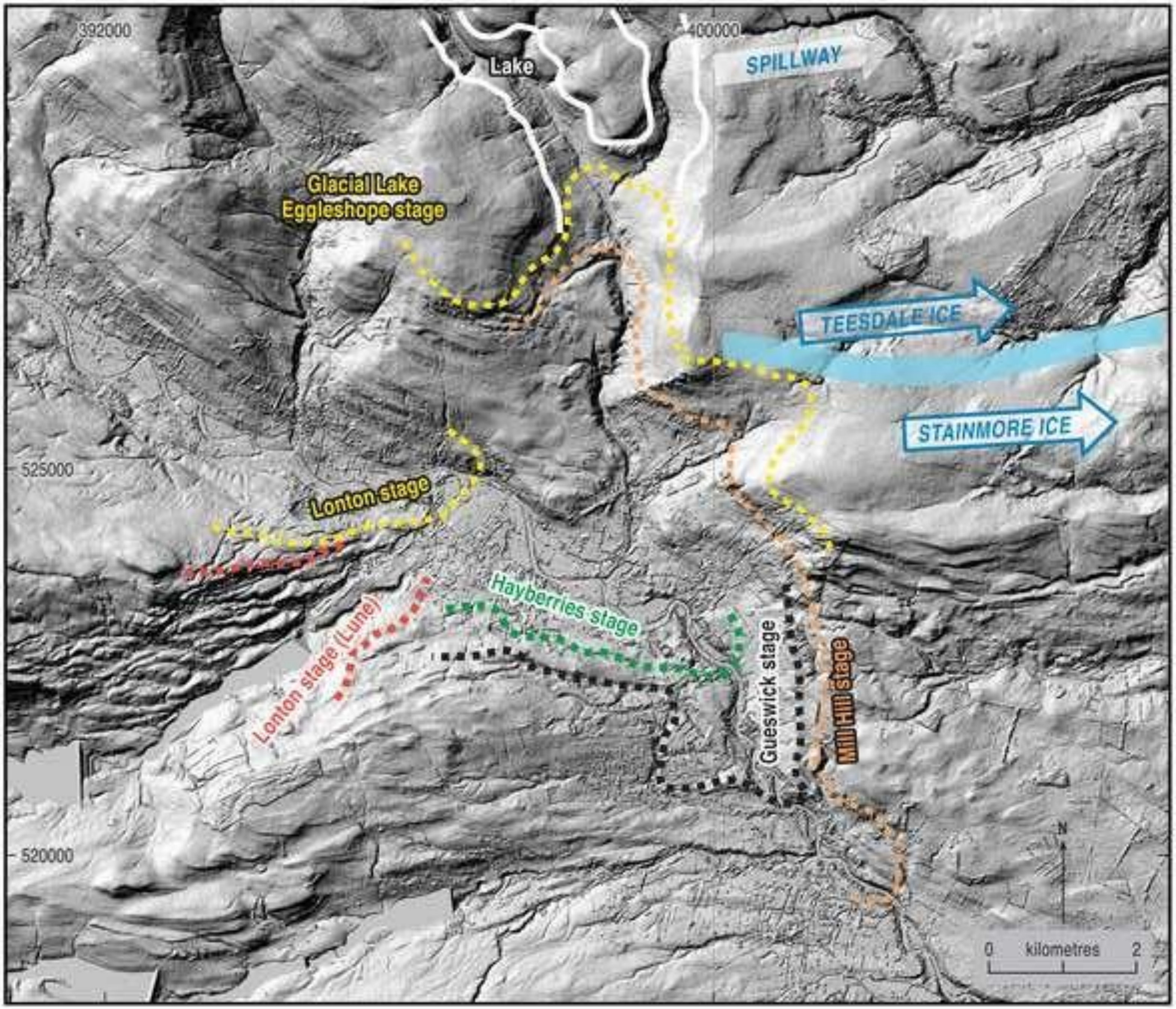
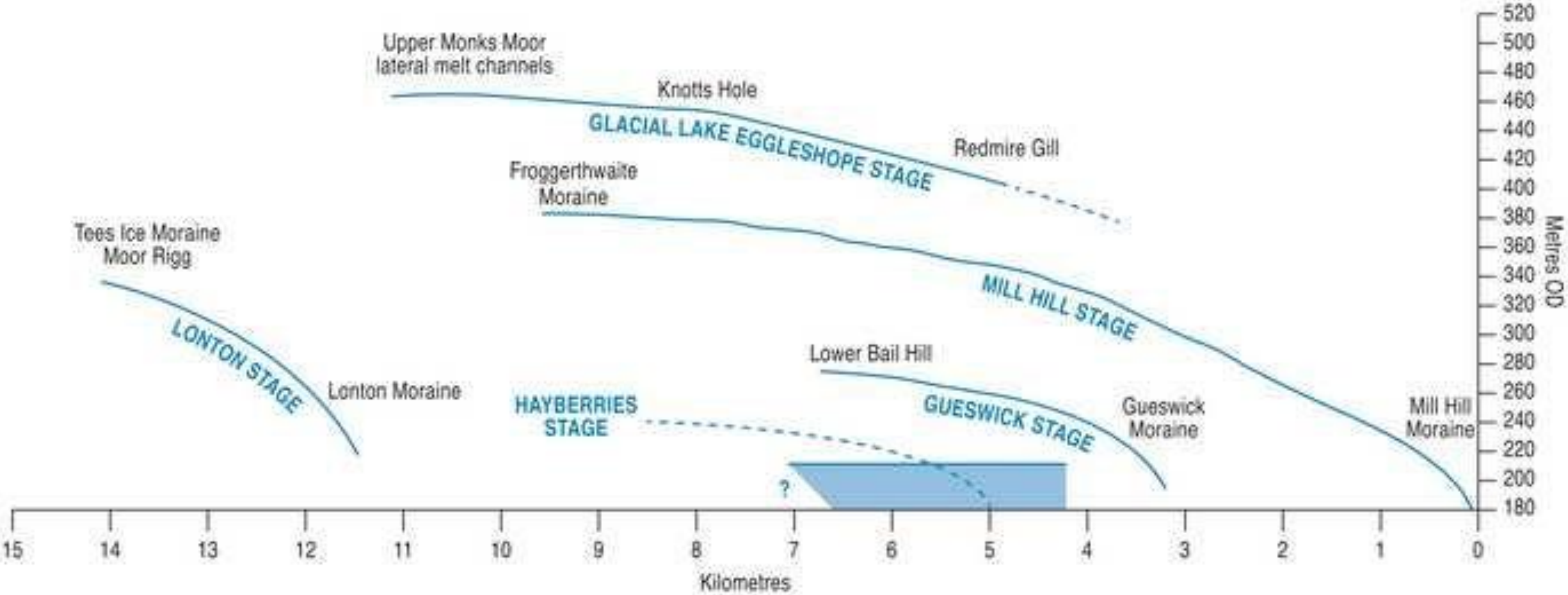


Figure 34
Click here to download high resolution image



e

Supplementary Information Figure 1

Click here to download high resolution imag e